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An investigation of the effect of direct water injection on detonation

Seibels, Robert Emmet, Jr.; Washington, Thomas, Jr.;
MacLachlan, John Roxburgh; Seibels, Robert Emmet;
Washington, Thomas; MacLachlan, John Roxburgh

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AN INVESTIGATION OF THE
EFFECT OF DIRECT WATER
INJECTION ON DETONATION

BY
ROBERT EMMET SEIBELS, JR.
THOMAS WASHINGTON, JR.
AND
J. R. MacLACHLAN

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AN INVESTIGATION OF THE EFFECT OF
DIRECT WATER INJECTION ON DETONATION

by

Comdr. R. E. Seibels, Jr., USN 1917-

Comdr. T. Washington, Jr., USN 1915-

LtCdr. J. R. MacLachlan, USN

Submitted in Partial Fulfillment of the
requirements for the
Degree of Master of Science
in
Aeronautical Engineering
from the
Massachusetts Institute of Technology
1946 ✓

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Cambridge, Massachusetts
1 June 1946

Professor George W. Swett
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

A thesis entitled "An Investigation of the Effect of Direct Water Injection on Detonation" is herewith submitted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering. .


Cambridge, Massachusetts
1 June 1945


Professor George E. Smith
Secretary of the Society
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

A thesis entitled "An Investigation of the Effect of
Direct Water Injection on Detonation" is herewith submitted
in partial fulfillment of the requirements for the degree
of Master of Science in Mechanical Engineering.

Respectfully,


J. H. Paine, Jr.
Master of Science
June 1, 1945


T. W. Lammiman, Jr.
Master of Science
June 1, 1945


J. P. Moore
Master of Science
June 1, 1945

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The following is a list of the names of the persons who have been identified as having been involved in the activities of the group, and the dates on which they were identified:

tion of the evidence presented by the entire staff of
the State Laboratory, Washington, D.C., and the
Federal Bureau of Investigation, Washington, D.C.
by Professor C. W. Taylor, Assistant Professor,
University of California, Berkeley, California.

AN INVESTIGATION OF THE EFFECT OF DIRECT WATER INJECTION ON DETONATION

SUMMARY

The purpose of this project was to investigate the effects of direct water injection on detonation. The following conclusions were reached:

1. The addition of water at a constant fuel-air ratio permits the attainment of higher indicated mean effective pressures without detonation. This effect is more pronounced for low fuel-air ratios than for high fuel-air ratios.
2. At a fixed water-fuel ratio, the fuel-air ratio at which the maximum detonation free indicated mean effective pressure occurs increases as compression ratio decreases.
3. At a constant isfc, detonation free imep increases with water-fuel ratio. At fuel-air ratios below .09, islc increases very rapidly with increase in imep while at fuel-air ratios above .09, islc decreases slightly with imep increase.
4. Increasing water-fuel ratio at low (cruising) fuel-air ratios results in a decrease in isfc, but at the expense of a prohibitive increase in islc.
5. Fuel is considerably more effective than water as an anti-detonant at low (cruising) fuel-air ratios.
6. At high (take-off) fuel-air ratios, water is effective as an anti-detonant, while the use of additional

RESULTS

The purpose of this report was to investigate the effect of direct versus indirect lighting on the growth of plants.

1. The addition of light to a constant dark-light regime resulted in a significant increase in plant height and leaf area. This effect was more pronounced in the low light regime than in the high light regime.

2. At a fixed water-potential level, the rate of growth was higher in the high light regime than in the low light regime. The presence of water potential as a limiting factor was also observed.

3. At a constant level of water potential, the rate of growth was higher in the high light regime than in the low light regime. This indicates that water potential is not the only factor limiting growth.

4. The results of this study indicate that the rate of growth is not only affected by light intensity but also by water potential. The effect of light intensity is more pronounced in the high light regime than in the low light regime.

5. The results of this study indicate that the rate of growth is not only affected by light intensity but also by water potential. The effect of light intensity is more pronounced in the high light regime than in the low light regime.

fuel for this purpose actually results in a decrease of imep.

7. Indicated thermal efficiency is not affected by the addition of water.

8. Water injection permits the use of higher compression ratios by increasing detonation free imep to take-off values. This permits the designer to take advantage of the greatly improved fuel economy in the cruising range resulting from the use of high compression ratios.

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AN INVESTIGATION OF THE EFFECT OF DIRECT WATER INJECTION ON DETONATION

INTRODUCTION

It is an established fact that, for a fixed inlet pressure and temperature, increase of compression ratio of an engine increases power output slightly but produces a decided improvement in fuel economy. Therefore, designers of internal combustion engines would desire to use high compression for the purpose of obtaining fuel economy. But increase of compression ratio is limited because of detonation at high powers. Thus, the attempt to improve fuel economy by increasing compression may render an engine unsuitable for use because of the reduction of power for take-off and full load.

The limitations of increased compression ratio on take-off and full load are now being improved by the addition of water to the fuel-air mixture. During the past war, the method of spraying water into the inlet manifold was used with considerable success. According to some reports, the power for take-off was increased by 15% to 30%. A second method of adding water to the fuel-air mixture would be by direct injection of water into the cylinder. This second method has had very little investigation and no practical use at the present date. It is the object of this project to investigate the effect on detonation of direct water injection into the cylinder.

It is an established fact that, for a fixed inlet pressure and temperature, increase of compression ratio of an engine increases power output slightly but increases frictional drag to a greater extent. Therefore, designers of internal combustion engines would prefer to use high compression for the purpose of obtaining best economy, but increase of compression ratio is limited because of adverse effects on engine life. Thus, the object is to improve fuel economy by increasing compression ratio without an undue maintenance for the purpose of the reduction of power for safe operation.

The investigation of the engine was continued until it was found that the cause of the trouble was the faulty timing of the valves. The valve gear was adjusted and the engine was run at various speeds. It was found that the engine ran smoothly at all speeds when the valves were correctly timed.

The project was conducted at the Sloan Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, by Comdr. R. F. Seibels, Jr., USN, Comdr. T. Washington, Jr., USN, and Lt. Comdr. J. E. MacLachlan, USN. Mr. W. A. Leary of the M.I.T. staff was supervisor.

EQUIPMENT

The test equipment included a variable-compression, one-cylinder Coordinating Fuel Research Engine delivering power to a dynamometer. Fuel vaporization was accomplished by spraying fuel into a heated vaporizing tank. An injection pump and an injection nozzle were used to spray water directly into the cylinder. Figs. 1, 2, 3, and 4 are photographs of the arrangement of equipment. Fig. 5 is a block diagram of the installation set-up.

The engine of this project was a standard variable-compression, one-cylinder CFR Engine. This engine had a 3.25 in. bore, a 4.5 in. stroke and a 37.33 cu. in. displacement. Compression could be set at any desired compression ratio between 4 and 10. This standard CFR Engine is fully described in Ref. 1.

The dynamometer was a 5 HP motor-generator set manufactured by the Star Electric Motor Company. It was used as a motor to turn over the CFR Engine for starting or motoring, and as a generator to absorb the power delivered by that engine.

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1. The first experiment involved a series of 100 trials, each consisting of a 10-second presentation of a stimulus, followed by a 10-second response period. The stimulus was a 10-second audio recording of a speech sample, and the response was a 10-second audio recording of a speech sample. The stimulus and response were presented simultaneously, and the subject was required to respond to the stimulus by producing a speech sample. The response was then compared to the stimulus, and the subject was informed of the result. The experiment was repeated 100 times, and the results were analyzed.

The engine of this project was a standard variable-compression, four-cylinder 151 engine. This engine had a 1.5 in. bore, a 4.1 in. stroke and a 7.7:1 compression ratio. Compression could be set at any desired compression ratio between 1 and 15. This standard 151 engine is built in 1961.

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The gasoline used in this experiment was standard 80 octane unleaded aviation gasoline. This gasoline was taken from the mains of the Sloan Laboratory and passed through a fuel rotometer to the fuel pump. A Bosch injection pump driven by a small electric motor forced the gasoline at high pressure through an injection nozzle into a heated vaporizing tank. A vernier adjustment on the Bosch pump allowed accurate control of fuel flow.

Air to the vaporizing tank could be taken either from the test room at atmospheric pressure, or from the laboratory high pressure main. A Nash Hytor L-5 Compressor driven by a Sprague Electrical Dynamometer supplied the high pressure air. The air was metered through a calibrated orifice and drawn into the vaporizing tank.

Distilled water was used for injection into the cylinder. This distilled water was stored in a one gallon glass jug. From the jug the water flowed by gravity to a constant level float chamber and thence through a water rotometer to the water pump. The water pump was an engine driven Bosch injection pump equipped with a vernier adjustment for close control of flow. The pump forced water at high pressure through a Bendix KC 50S1 injection nozzle (Fig. 6) into the cylinder at a point opposite the spark plug.

Detonation was detected by a detonation pickup and oscillograph. The pickup was one of the pressure type, being

sensitive to the rate of change of pressure (dp/dt). The oscillograph was a Dumont 208 Cathode-Ray Oscillograph.

Other apparatus used in preparation for this experiment included balance scales, MIT Pressure-Crank Machine, and MIT Transfer Machine which transferred pressure-crank readings to pressure volume. The latter two machines are described in Appendix II of Ref. 2 and Appendix B of Ref. 3, respectively.

The water injection equipment of this experiment leaves much to be desired. The time of the start of injection can be accurately controlled. But, unfortunately, the length of time of injection varies with the amount of water injected. Detonation takes place somewhere near to the same crank angle for all powers and fuel-air ratios. It would be desirable to have the angle of injection time remain constant no matter what the rate of water flow, and to so adjust the time of injection as to best suppress detonation. With the present apparatus, some of the benefit is lost because the time of mid-point of injection varies with water flow. Optimum utilization of water cannot be realized because at low and moderate flow rates, some of it may be injected too early for best detonation suppression, while at high flow rates, part of the water is injected too late to be effective.

PRELIMINARY PROCEDURE

It was necessary, prior to the commencement of this investigation, to devote considerable time and labor to the arrangement of the test apparatus shown in Figs. 1 through 4. The purpose was two-fold: first, to eliminate or to reduce as far as possible the effects of those variables not pertinent to this investigation; and second, to permit accurate control of all essential variables.

As further preliminaries it was necessary to calibrate both the fuel and water rotometers, the water injection apparatus, and to calibrate the dynamometer mercury manometer in terms of indicated mean effective pressure. As a final preliminary to this investigation, the water injection apparatus was timed to insure start of injection at the desired crank angle.

Calibration curves of the fuel and water rotometers made from the data of Table I appear in Fig. 7. The method of calibration followed in both cases consisted essentially of weighing the amount of liquid which passed through the rotometer in a measured interval of time, during which the rotometer setting was maintained at a constant value. The mass flow per second was calculated and plotted against rotometer setting.

To calibrate the dynamometer mercury manometer, indicator cards were taken using MIT Pressure Crank Angle Machine,

VERIFICATION PROCEDURE

It was necessary, prior to the commencement of this investigation, to make a preliminary study and report on the character of the data obtained from the field. The purpose of this study was to determine the nature of the data and to determine the methods of collection and analysis. The results of this study are presented in the following report.

The first step in the verification procedure is the collection of data. This is done by the use of a questionnaire which is distributed to the subjects. The questionnaire is designed to obtain information on the subjects' behavior and on the factors which influence their behavior. The data obtained from the questionnaire are then analyzed to determine the relationship between the variables.

The second step in the verification procedure is the analysis of the data. This is done by the use of statistical methods. The data are first organized into a table and then analyzed by the use of the chi-square test. The results of the analysis are then presented in the form of a graph.

The third step in the verification procedure is the interpretation of the results. This is done by the use of the results of the analysis to determine the relationship between the variables. The results are then presented in the form of a graph.

The fourth step in the verification procedure is the conclusion. This is done by the use of the results of the analysis to determine the relationship between the variables. The results are then presented in the form of a graph.

following the procedure outlined in Ref. 2, simultaneously with mercury manometer readings. From the indicator cards, indicated mean effective pressure was determined, using MIT Transfer Machine to transfer pressure crank values to pressure volume values. (Ref. 3). A plot of indicated mean effective pressure versus inches of mercury made from data of Table II appears in Fig. 8.

The calibration of the water injection apparatus in terms of water rotometer reading and duration of water spray in degrees of crank angle, α , is shown in Fig. 9. The start of the spray was set to occur at top center by means of an adjustable coupling on the water pump drive shaft and a stroboscope timed to flash at top center. Top center, itself, was determined by the standard CFR Engine calibrated brass spark timing ring and a flashing neon light. It was found as shown in Fig. 9 that varying the water rotometer setting varied the duration of injection in degrees of crank angle, although the start of injection remained fixed at top center.

In order to determine the optimum angle at which to start injection, the following steps were taken. The compression ratio was set at 6.6, and the fuel-air and water-fuel ratios were set arbitrarily at .08 and .8, respectively. The crank angle at which injection starts and the mass rate of air flow were then varied until, by trial and error, the maximum indicated mean effective pressure without detonation

Following the pressure reading in Fig. 1, simultaneously
the pressure was measured. From the pressure curve,
indicated with effective pressure was determined, which
the pressure reading in transfer pressure curve is
pressure value curve, Fig. 1. A plot of indicated
effective pressure versus time of pressure curve from Fig.
at Table II appears in Fig. 2.

The calibration of the water injection apparatus is
shown in water injection reading and location of water spray
in degree of curve curve, α , is shown in Fig. 3. The
start of the spray was at about 10 degrees of curve
of an adjustable reading on the water pump drive shaft and
a reference line is shown in Fig. 4. The spray, it
self, was determined by the reading of the water
pump drive shaft and a straight line is shown. It was
found as shown in Fig. 5 that varying the water injection
reading varied the location of injection in degree of curve
curve, although the spray of injection remained fixed at 10
degrees.

In order to determine the optimum angle of water
spray injection, the following tests were made. The
injection angle was set at 10, 15, and the fuel-air ratio
fuel ratio was set respectively at .08 and .1, respectively.
The spray angle at water injection angle and the water ratio
of the flow rate were varied until, by trial and error, the
maximum indicated mean effective pressure without detonation

was obtained. The optimum angle corresponding to this condition was thus found to be 18° after top center. In all subsequent tests in which water was utilized, injection was started at this point. It is realized that this 18° setting probably was not the optimum angle for the entire range of fuel-air ratios and compression ratios. This setting was selected as a compromise in order to reduce the number of variables of the experiment. Since the conditions imposed during selection of this 18° angle for start of injection were about average, the setting is probably near optimum for the vast majority of the readings of this project.

PROCEDURE

The general plan adhered to in this investigation appears below. The following set of operating conditions was adopted as standard: oil temperature 160°F , oil pressure 35 psi., inlet temperature 140°F , jacket temperature 212°F , and engine speed 1200 RPM. The compression ratio was set at 6.2. Test data were taken for five fuel-air ratios - .064 (good cruising), .07, .08 (best power), .09 and .10. For each fuel-air ratio detonation limited indicated mean effective pressure was determined by means of a cathode-ray oscillograph for water-fuel ratios of from 0 to over 1.0. Curves of detonation limited indicated mean effective pressure at various fuel-air ratios are plotted in Fig. 10 from the data of Table III.

The procedure described above was repeated for compression ratios of 6.6, 7.0, and 7.4. The resulting data obtained appear in Tables IV through VI. The corresponding curves are drawn in Figs. 11 through 13.

A warming up period was required as a daily preliminary to the making of record runs. The CFR Engine required approximately one hour before steady operating conditions were obtained with respect to oil pressure and temperature, jacket temperature, inlet pressure, and particularly inlet temperature. To reduce the delay involved in warming up, oil temperature could be raised by means of an electric oil heater in the crank case and engine jacket temperature by means of a steam bleed. During the warm-up and actual runs, inlet temperature was regulated by varying the amount of steam admitted to the jacket surrounding the vaporizing tank.

When steady operating conditions were obtained and with the compression ratio set at 6.2, a fuel-air ratio of .064 (without water) was set by simultaneously varying the mass rates of flow of both air and fuel until, by trial and error, the desired fuel-air ratio was obtained just as incipient detonation occurred. In this way, the detonation limited indicated mean effective pressure at a zero water-fuel ratio for these conditions was obtained. The mass rate of air flow was then increased. At the same time, the resulting detonation was suppressed by the introduction of an excessive amount of water. Next, the mass rate of fuel flow was increased un-

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til a fuel-air ratio of .064 was again obtained. By reducing the amount of water until a condition of incipient detonation again existed, the detonation limited indicated mean effective pressure and the corresponding water-fuel ratio were readily determined. The compression ratio was held constant at 6.2, and the above procedure followed for fuel-air ratios of .07, .08, .09, and .10. In this manner the family of curves shown in Fig. 10 were determined.

The curves of Figs. 11, 12, and 13 were determined in the same manner from the data of Tables IV, V, and VI. The compression was varied through 6.6, 7.0, and 7.4. In order to obtain more readily comparable results the same series of fuel-air ratios were used in each case.

Additional points at a zero water-fuel rate were obtained at a compression ratio of 7.4, for fuel-air ratios of .075, .085, .095, and .11 in order to compare the effectiveness of water versus fuel as anti-detonants. This data is included in Table VI.

RESULTS AND DISCUSSION

The effect of water-fuel ratio on indicated mean effective pressure at compression ratios of 6.2, 6.6, 7.0, and 7.4 is shown in Figs. 10, 11, 12, and 13, respectively. To obtain readily comparable results, the following fuel air ratios were used throughout: .064, .07, .08, .09, and .10. In Fig. 14 are shown the relative effects of fuel and water as detonation suppressors. A cross plot at a constant indicated mean effective pressure of 115 p.s.i.a., of compression ratio versus water-fuel ratio at various fuel-air ratios is shown in Fig. 15.

It may be seen from Fig. 10 that the addition of water accomplished at a constant fuel-air ratio, permits the attainment of a higher indicated mean effective pressure without detonation. It may be seen further from Fig. 10 that the slopes of the curves became progressively shallower as the mixture becomes richer. This means that the effect of water addition is more pronounced at low fuel-air ratios. Similar trends are noted for all compression ratios investigated. (Figs. 11, 12, and 13).

At a compression ratio of 7.4 (Fig. 13) for any given water-fuel ratio, the maximum detonation free indicated mean effective pressure occurs at a fuel-air ratio of .09. As the compression ratio is decreased (Figs. 12, 11, and 10) the maximum indicated mean effective pressure for a given water-

fuel ratio appears to occur at progressively higher fuel-air ratio. Thus, for a compression ratio of 6.2, the optimum detonation free fuel-air ratio appears to be slightly greater than .10. This phenomenon is considered to be characteristic of this 80-octane unleaded aviation gasoline, and would not necessarily recur for another gasoline.

Superimposed on Fig. 13 are curves of constant indicated specific fuel consumption (isfc) and indicated specific liquid (fuel plus water) consumption (islc). An examination of the figure shows that at a constant isfc, detonation free imep obtainable increases with water-fuel ratio. However, this increase of imep at a constant isfc is obtained at the expense of a considerable increase in islc, as long as the fuel-air ratio remains below .09. When the fuel-air ratio exceeds .09, increasing the water-fuel ratio at a constant isfc is accompanied by two effects: first, a slight increase in imep; and second, a slight decrease in islc. Further, at a given water-fuel ratio and at a fuel-air ratio of .10 or greater, a decrease of fuel-air ratio results in both an increase in detonation free imep and a decrease in islc. Translating the above into practical applications, although increasing water fuel for a given cruise power output results in a lower isfc, the increase in islc is prohibitive.

Continuing in the same vein, Fig. 15 was plotted in order to compare the effects of additional water and fuel as detonation suppressors, both at a cruising fuel-air ratio and at a fuel-air ratio of .09, which was considered to be within the take-off range. Fuel was found to be considerably more effective than water at the low fuel-air ratio. The reverse was true at the high fuel-air ratio. Actually the use of additional fuel as a detonation suppressor at the high fuel-air ratio resulted in a decrease of imep, while the addition of water permits an increase in imep. It is evident that in order to attain high values of imep (in this case, 115) water must be used since these values cannot be attained with fuel alone.

By classical theory, the indicated thermal efficiency is a function both of compression ratio and fuel-air ratio. For a fixed compression ratio and fuel-air ratio, indicated thermal efficiency would be constant if the addition of water had no effect. Tables III through VI show that for a given fuel-air ratio and compression ratio, the indicated thermal efficiency remains constant regardless of the water-fuel ratio. It is therefore concluded that indicated thermal efficiency is not affected by the addition of water.

High compression ratios with their resulting high efficiencies are desirable in order to give fuel economy in the cruise range, but take-off powers are limited by detonation of the fuel-air mixture. The advantage of water in-

Continuing in the same vein, Fig. 15 was plotted in order to compare the effects of additional water and fuel on the indicated horsepower, both at a standard fuel-air ratio and at a fuel-air ratio of .65, which was considered to be within the limits of range. Fuel was found to be adversely more effective than water at the low fuel-air ratio. The reason was true as the high fuel-air ratio, namely the use of additional fuel as a replacement for water at the high fuel-air ratio resulted in a decrease of power, while the addition of water results in increase in power. It is evident that in order to obtain high values of power (in this case, 150) water must be used in place of fuel.

In general theory, the indicated thermal efficiency is a function both of compression ratio and fuel-air ratio. For a fixed compression ratio and fuel-air ratio, indicated thermal efficiency would be constant if the addition of water had no effect. Hence the theory of water for a given fuel-air ratio and compression ratio, the indicated thermal efficiency would be constant regardless of the fuel-air ratio. It is therefore concluded that indicated thermal efficiency is not affected by the addition of water.

High compression ratios with fuel resulting also in efficiencies are desirable in order to give fuel economy in the engine itself. The lower the power and lower the efficiency of the fuel-air mixture. The efficiency of water in-

jection is that it permits use of high compression ratios, while providing sufficient power for take-off. The curves of Fig. 15 were drawn to illustrate this effect. If an imep of 115 p.s.i.a. was required for the take-off, the compression ratio would be limited to approximately 6.7 in the absence of water. By using a water-fuel ratio of about 1.3, the compression ratio may be increased to 7.4. Since take-off powers would be used for only a short period, the high water-fuel ratio of 1.3 is not prohibitive. Similar trends are apparent for the remaining fuel-air ratios considered. Thus, the airplane designer, by using the high compression ratios and accepting the high water-fuel ratios required for take-off, may obtain greatly improved fuel economy in the cruising range.

In conclusion it may be stated that the percent increase in imep obtainable by using a water-fuel ratio of about 1.0 is in the order of 15%. Thus, the method of direct water injection used in this investigation compares favorably with the method of adding water to the induction system. Had the mechanics of direct water injection used herein been more refined, this method might have proven its superiority over the water-into-induction-system method.

CONCLUSIONS

As a result of this investigation of the effect on detonation of direct water injection into the cylinder of an engine operating on 80 octane unleaded aviation gasoline, the following conclusions were reached:

1. The addition of water at a constant fuel-air ratio permits the attainment of higher indicated mean effective pressures without detonation. This effect is more pronounced for low fuel-air ratios than for high fuel-air ratios.
2. At a fixed water-fuel ratio, and for this gasoline, the fuel-air ratio at which the maximum detonation free indicated mean effective pressure occurs increases as compression ratio decreases.
3. At a constant isfc, detonation free imep increases with water-fuel ratio. At fuel-air ratios below .09, islc increases very rapidly with increase in imep while at fuel-air ratios above .09, islc decreases slightly as imep increases.
4. Increasing water-fuel ratio at low (cruising) fuel-air ratios results in a decrease in isfc, but at the expense of a prohibitive increase in islc.
5. Fuel is considerably more effective than water as an anti-detonant at low (cruising) fuel-air ratios.

CONCLUSIONS

As a result of this investigation of the effect of
exposure to light on the rate of growth of
the various species of algae, it was found that
the rate of growth was highest in the light and
lowest in the dark.

1. The addition of light to a culture of algae
resulted in a rapid increase in the rate of
growth. This increase was observed in all
species of algae tested. The rate of growth
was highest in the light and lowest in the
dark.

2. The rate of growth of algae was highest in
the light and lowest in the dark. This was
observed in all species of algae tested.
The rate of growth was highest in the light
and lowest in the dark.

3. The rate of growth of algae was highest in
the light and lowest in the dark. This was
observed in all species of algae tested.
The rate of growth was highest in the light
and lowest in the dark.

4. The rate of growth of algae was highest in
the light and lowest in the dark. This was
observed in all species of algae tested.
The rate of growth was highest in the light
and lowest in the dark.

6. At high (take-off) fuel-air ratios, water is effective as an anti-detonant, while the use of additional fuel for this purpose actually results in a decrease of imep.
7. Indicated thermal efficiency is not affected by the addition of water.
8. Water injection permits the use of higher compression ratios by increasing detonation free imep to take-off values. This permits the designer to take advantage of the greatly improved fuel economy in the cruising range resulting from the use of high compression ratios.

2. At this (June-1977) time, when the effects
of the anti-inflation, while the use of additional fuel for
this purpose actually results in a reduction of fuel.
3. Indicated thermal efficiency is not affected by the ad-
dition of water.

4. Water injection results in the use of higher compression
ratio by increasing compression from 14.5 to 16.5-17
ratio. This results in the engine to have advantage of
the greatly improved fuel economy in the engine range
resulting from the use of high compression ratio.

The engine is a four-cylinder, four-stroke, water-cooled, diesel engine, with a displacement of 1.8 liters (110 cubic inches). The engine is equipped with a mechanical fuel injection system, and the fuel is supplied by a high-pressure pump. The engine is designed to operate at a maximum speed of 2400 rpm, and the maximum power output is 100 hp (74.6 kW) at 2400 rpm. The engine is equipped with a water injection system, which is used to improve the engine's performance and fuel economy. The water injection system consists of a water pump, a water filter, and a water injection valve. The water is injected into the combustion chamber through the water injection valve, and the water is atomized by the high-pressure fuel spray. The water injection system is controlled by a water injection control valve, which is operated by a water injection control solenoid. The water injection system is used to improve the engine's performance and fuel economy by increasing the compression ratio and reducing the engine's operating temperature. The water injection system is also used to improve the engine's emissions by reducing the amount of unburned fuel and carbon monoxide in the exhaust gas. The water injection system is a simple and effective way to improve the engine's performance and fuel economy, and it is a common feature on many diesel engines.

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10. W. E. Ruppel -- 1944 Edition.

Formulae for Computations

CFR Engine Data

$$\text{Bore} = 3.25" \quad \text{Piston Area} = 8.296 \text{ in}^2$$

$$\text{Stroke} = 4.50" \quad \text{Displacement Volume} = 37.33 \text{ in}^3$$

$$\text{rpm} = 1200 \text{ (constant)}$$

$$\text{imep} = \frac{\text{Area P-V Diagram}}{5} \times \text{Spring Constant, psia}$$

$$\text{IHP} = \frac{\text{imep} \times \text{Piston Area} \times \frac{\text{Stroke}}{12} \times \frac{\text{rpm}}{2}}{33000} = .0566 \times \text{imep}$$

$$\text{ISFC} = \frac{\text{lb. fuel/hr.}}{\text{IHP}} = \frac{\dot{M}_f \times 3600}{\text{IHP}}$$

$$\text{ISWC} = \frac{\text{lb. water/hr.}}{\text{IHP}} = \frac{\dot{M}_w \times 3600}{\text{IHP}}$$

$$\text{ISLC} = \frac{\text{lb. Liquid/hr.}}{\text{IHP}} = \frac{3600}{\text{IHP}} (\dot{M}_f + \dot{M}_w) = \text{ISFC} + \text{ISWC}$$

$$\eta_i = \frac{\text{IHP} \times 2545}{3600 \times \dot{M}_f \times E_c} = \frac{\text{IHP} \times 2545}{\dot{M}_f \times 3600 \times 19270} = \frac{\text{IHP}}{27250 \dot{M}_f}$$

Formulas for Calculations

1. Basic Data

Base = 1.000
Height = 1.000
Distance from Base to Top = 0.500

Top = 1.000 (assumed)

Top = 1.000 (assumed) + 0.500 (Distance from Base to Top)

$$Top = 1.000 + \frac{0.500 \times 1.000}{1.000} = 1.500$$

$$Top = 1.500 + \frac{0.500 \times 1.000}{1.000} = 2.000$$

$$Top = 2.000 + \frac{0.500 \times 1.000}{1.000} = 2.500$$

$$Top = 2.500 + \frac{0.500 \times 1.000}{1.000} = 3.000$$

$$Top = 3.000 + \frac{0.500 \times 1.000}{1.000} = 3.500$$

Units

Area P-V Diagram	=	Square inches
Spring Constant	=	Pounds per inch
i_{mep}	=	Indicated mean effective pressure, psia
IHP	=	Horsepower
\dot{M}_f	=	Fuel flow, pounds per second
\dot{M}_w	=	Water flow, pounds per second
ISFC	=	Indicated Specific Fuel Consumption, $\frac{lb/hr}{IHP}$
ISWC	=	Indicated Specific Water Consumption, $\frac{lb/hr}{IHP}$
ISLC	=	Indicated Specific Liquid Consumption, $\frac{lb/hr}{IHP}$
η_1	=	Indicated Thermal Efficiency

TABLE I

Calibration of Fuel and Water Rotometers

Water Rotometer Calibration
3/14/46 T° = 81

<u>Roto Reading</u>	<u>Wt Gms</u>	<u>Time Sec</u>	<u>lbs/sec</u>
7.55	10	72.7	.000303
8.1	10	64.35	.000348
6.6	10	105.95	.000208
7.1	10	94.3	.000234
17.1	20	29.9	.001473
14.95	20	39.0	.00113
12.8	20	53.8	.00082
5.1	10	229.5	.000096
15.9	20	34.8	.001268
13.3	20	46.85	.00094
10.1	20	82.95	.000532
13.8	20	45.55	.000969
11.05	20	70.25	.000625
8.2	10	65.5	.000337
8.75	10	56.75	.000389
9.4	10	47.8	.000461
5.65	10	151.2	.000146
5.8	10	141.65	.000156
12.3	20	57.7	.000764
11.1	20	70	.00063
10.65	20	76.1	.000595
9.6	10	56.25	.000392
11.4	20	66.2	.000666
12.1	20	59.4	.000741
7.1	10	96.65	.000228
7.7	10	72.75	.000303
6.25	10	120.35	.000183
13.65	20	45.3	.000973
14.5	20	41.4	.001064
15.5	20	36.1	.00122
13.3	20	47.7	.000925
13.8	20	45.7	.000965
13.65	20	45.6	.000966
13.3	20	49.05	.000900

Gasoline Rotometer Calibration
3/15/46 T° = 66

<u>Roto Reading</u>	<u>Wt Gms</u>	<u>Time Sec</u>	<u>lbs/sec</u>
9.7	20	38.3	.00115
8.95	20	43.4	.001018
8.45	20	46.7	.000943
7.85	20	50.4	.000874
7.25	20	55.8	.000789
5.5	20	79.6	.000553
5.9	20	71.9	.000613
6.35	20	64.6	.000681
6.8	10	29.6	.000745
5.15	10	42.5	.000519
3.65	10	66.2	.000332
4.2	10	53.45	.000412
10.4	20	35.5	.001242
11.05	20	33.15	.001329
11.45	20	29.8	.00148
11.8	20	29.55	.001491
12.05	20	28.75	.001535
4.4	10	50.35	.000439
6.25	10	33.9	.000651
6.7	10	31.65	.000696
6.85	10	30.3	.000729
8.95	20	21.5	.001026
9.45	20	19.6	.001124
10.0	20	18.1	.001218
8.9	20	19.3	.001022
11.4	20	15.75	.0014
10.65	20	15.95	.00138
8.05	20	24.5	.0009
7.6	20	26.1	.000845
9.25	20	20.65	.001065
10.3	20	17.8	.001239
9.75	20	19.3	.001141
10.1	20	18.3	.0012

TABLE I

Calibration of Test and Pilot Instruments

Pilot Instrument Calibration No. 11 3/14/40				Test Instrument Calibration No. 22 3/14/40			
Reading	psi	Bar	psi	Reading	psi	Bar	psi
7.53	10		9.7	7.53	10		9.7
8.1	10		8.75	8.1	10		8.75
8.6	10		8.15	8.6	10		8.15
9.1	10		7.5	9.1	10		7.5
9.7	10		6.85	9.7	10		6.85
10.1	10		6.2	10.1	10		6.2
10.4	10		5.55	10.4	10		5.55
10.8	10		4.9	10.8	10		4.9
11.1	10		4.25	11.1	10		4.25
11.5	10		3.6	11.5	10		3.6
11.8	10		2.95	11.8	10		2.95
12.1	10		2.3	12.1	10		2.3
12.4	10		1.65	12.4	10		1.65
12.8	10		1.0	12.8	10		1.0
13.1	10		0.35	13.1	10		0.35
13.5	10		-0.3	13.5	10		-0.3
13.8	10		-0.95	13.8	10		-0.95
14.1	10		-1.6	14.1	10		-1.6
14.5	10		-2.25	14.5	10		-2.25
14.8	10		-2.9	14.8	10		-2.9
15.1	10		-3.55	15.1	10		-3.55
15.5	10		-4.2	15.5	10		-4.2
15.8	10		-4.85	15.8	10		-4.85
16.1	10		-5.5	16.1	10		-5.5
16.5	10		-6.15	16.5	10		-6.15
16.8	10		-6.8	16.8	10		-6.8
17.1	10		-7.45	17.1	10		-7.45
17.5	10		-8.1	17.5	10		-8.1
17.8	10		-8.75	17.8	10		-8.75
18.1	10		-9.4	18.1	10		-9.4
18.5	10		-10.05	18.5	10		-10.05
18.8	10		-10.7	18.8	10		-10.7
19.1	10		-11.35	19.1	10		-11.35
19.5	10		-12.0	19.5	10		-12.0
19.8	10		-12.65	19.8	10		-12.65
20.1	10		-13.3	20.1	10		-13.3
20.5	10		-13.95	20.5	10		-13.95
20.8	10		-14.6	20.8	10		-14.6
21.1	10		-15.25	21.1	10		-15.25
21.5	10		-15.9	21.5	10		-15.9
21.8	10		-16.55	21.8	10		-16.55
22.1	10		-17.2	22.1	10		-17.2
22.5	10		-17.85	22.5	10		-17.85
22.8	10		-18.5	22.8	10		-18.5
23.1	10		-19.15	23.1	10		-19.15
23.5	10		-19.8	23.5	10		-19.8
23.8	10		-20.45	23.8	10		-20.45
24.1	10		-21.1	24.1	10		-21.1
24.5	10		-21.75	24.5	10		-21.75
24.8	10		-22.4	24.8	10		-22.4
25.1	10		-23.05	25.1	10		-23.05
25.5	10		-23.7	25.5	10		-23.7
25.8	10		-24.35	25.8	10		-24.35
26.1	10		-25.0	26.1	10		-25.0
26.5	10		-25.65	26.5	10		-25.65
26.8	10		-26.3	26.8	10		-26.3
27.1	10		-26.95	27.1	10		-26.95
27.5	10		-27.6	27.5	10		-27.6
27.8	10		-28.25	27.8	10		-28.25
28.1	10		-28.9	28.1	10		-28.9
28.5	10		-29.55	28.5	10		-29.55
28.8	10		-30.2	28.8	10		-30.2
29.1	10		-30.85	29.1	10		-30.85
29.5	10		-31.5	29.5	10		-31.5
29.8	10		-32.15	29.8	10		-32.15
30.1	10		-32.8	30.1	10		-32.8
30.5	10		-33.45	30.5	10		-33.45
30.8	10		-34.1	30.8	10		-34.1
31.1	10		-34.75	31.1	10		-34.75
31.5	10		-35.4	31.5	10		-35.4
31.8	10		-36.05	31.8	10		-36.05
32.1	10		-36.7	32.1	10		-36.7
32.5	10		-37.35	32.5	10		-37.35
32.8	10		-38.0	32.8	10		-38.0
33.1	10		-38.65	33.1	10		-38.65
33.5	10		-39.3	33.5	10		-39.3
33.8	10		-39.95	33.8	10		-39.95
34.1	10		-40.6	34.1	10		-40.6
34.5	10		-41.25	34.5	10		-41.25
34.8	10		-41.9	34.8	10		-41.9
35.1	10		-42.55	35.1	10		-42.55
35.5	10		-43.2	35.5	10		-43.2
35.8	10		-43.85	35.8	10		-43.85
36.1	10		-44.5	36.1	10		-44.5
36.5	10		-45.15	36.5	10		-45.15
36.8	10		-45.8	36.8	10		-45.8
37.1	10		-46.45	37.1	10		-46.45
37.5	10		-47.1	37.5	10		-47.1
37.8	10		-47.75	37.8	10		-47.75
38.1	10		-48.4	38.1	10		-48.4
38.5	10		-49.05	38.5	10		-49.05
38.8	10		-49.7	38.8	10		-49.7
39.1	10		-50.35	39.1	10		-50.35
39.5	10		-51.0	39.5	10		-51.0
39.8	10		-51.65	39.8	10		-51.65
40.1	10		-52.3	40.1	10		-52.3

TABLE II

Calibration of Hydraulic Scale

Inches of Mercury vs. IMEP

<u>" Hg.</u>	<u>IMEP</u>
16.7	98.0
19.3	107.6
19.8	114.8
26.3	139.2
29.5	149.6

Table II

Calculated values of the ratio of the

number of atoms to the number of

atoms

atoms

0.00

0.00

0.01

0.01

0.02

0.02

0.03

0.03

0.04

0.04

M.I.T. AERO ENGINE LABORATORY

ENGINE C F R BORE 3 1/4 STROKE 4 1/2 COMPRESSION RATIO 6.2

Table III

REMARKS	DATE	TIME	R.H.M.	TEMP.		OIL PRESS	P _i	P _e	T _i	AIR CONS.	FUEL CONS.	F/A	S.A.	T _i	FUEL ROTO	ROOM TEMP.	BAR. CORR.	H ₂ O ROTO	M _w	W/F	H ₁	IMEP	HP	η _i	ISFC	ISWEC	ISLC																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
				OIL	JAC																								4/10/46	1732	13	1200	160	212	35	30.105	ATM	543	.01011	.000646	.064	25	138	6.20	81	30.105	0	0	0	17.3	101.8	5.76	3265	403	0	403		"	1741	14	"	"	"	"	"	"	"	.0103	.000659	"	"	142	6.30	"	"	7.5	.000274	.416	1785	104	5.88	327	403	.168	.571		"	1745	15	"	"	"	"	"	"	544	.0105	.000671	"	"	141	6.39	"	"	8.5	.000366	.545	1855	106.8	6.04	330	399	.218	.617		"	1754	16	"	"	"	"	"	"	"	.01069	.000684	"	"	"	6.48	"	"	10.0	.000516	.755	1935	110	6.23	3335	396	.298	.694		"	1803	17	"	"	"	"	"	"	"	.01097	.000701	"	"	"	6.62	"	"	10.5	.000570	.813	1945	112.3	6.36	332	397	.322	.719		4/18/46	1222	1	"	"	"	33	30.375	"	546	.01095	.000767	.07	"	142	7.09	85	30.045	0	0	0	19.70	111.3	6.30	301	438	0	438		"	1401	5	"	157	"	34	30.375	"	544	.01124	.000786	"	"	141	7.23	87	"	5.6	.000135	.172	2035	114	6.45	301	438	.075	.503		"	1425	6	"	"	"	"	30.375	"	545	.01144	.000801	"	"	140	7.34	"	"	8.7	.000305	.481	2065	115.2	6.53	299	442	.212	.654		"	1531	7	"	"	"	"	30.375	"	"	.01168	.000817	"	"	"	7.47	"	"	10.3	.000552	.676	2160	118.9	6.725	302	438	.246	.734		"	1540	8	"	"	"	"	30.375	"	"	.01204	.000842	"	"	138	7.63	"	"	11.8	.000701	.833	2240	122.2	6.91	301	438	.365	.803		"	1550	9	"	"	"	"	30.645	"	"	.01232	.000862	"	"	140	7.78	"	"	13.8	.000988	1.123	2385	127.8	7.10	307	432	.485	.917		"	1232	2	"	160	"	"	30.645	"	"	.01261	.00101	.08	"	"	8.85	85	"	0	0	0	23.00	124.5	7.045	256	516	0	516		"	1508	10	"	157	"	33	30.345	"	"	.01288	.001029	"	"	"	8.98	87	"	7.5	.000274	.266	2375	127.5	7.21	257	514	.137	.651		"	1516	11	"	"	"	"	30.375	"	"	.01310	.001048	"	"	138	9.10	"	"	11.3	.000652	.622	2445	130.3	7.375	258	512	.318	.830		"	1528	12	"	"	"	"	30.345	"	"	.01322	.001057	"	"	142	9.17	"	"	13.0	.000857	.812	2520	133.3	7.55	262	523	.408	.911		"	1540	13	"	160	"	32	30.095	"	544	.01369	.001094	"	"	138	9.38	"	"	14.4	.001052	.962	2610	136.7	7.73	259	510	.491	1.001		"	1549	14	"	"	"	"	30.375	"	"	.01400	.001122	"	"	140	9.55	"	"	15.7	.001244	1.108	2685	139.8	7.91	258	511	.567	1.078		"	1302	3	"	157	"	35	30.045	"	542	.01343	.001209	.09	"	138	10.08	83	"	0	0	0	24.75	131.4	7.44	226	585	0	585		"	1606	15	"	160	"	32	30.375	"	544	.01400	.001260	"	"	140	10.42	87	"	11.5	.000274	.535	2625	137.3	7.77	226	584	.312	.896		"	1614	16	"	"	"	"	30.045	"	"	.01384	.001247	"	"	138	10.33	"	"	9.9	.000505	.405	2570	135.2	7.65	225	587	.238	.825		"	1622	17	"	"	"	"	30.395	"	"	.01357	.001221	"	"	"	10.17	"	"	6.2	.000115	.152	2515	133.1	7.53	226	584	.089	.873		"	1632	18	"	"	"	"	30.245	"	"	.01438	.001243	"	"	140	10.63	"	"	14.0	.000997	.771	2695	140.3	7.94	225	587	.452	1.039		"	1639	19	"	"	"	"	30.045	"	"	.01466	.001319	"	"	138	10.78	"	"	15.5	.001245	.922	2740	142.2	8.05	224	590	.543	1.133		"	1320	4	"	157	"	35	"	"	542	.01389	.001389	.10	"	139	11.18	85	"	0	0	0	25.25	133.5	7.55	1944	.662	0	.662		"	1655	20	"	160	"	32	30.375	"	544	.01421	.001431	"	"	139	11.38	87	"	8.7	.000384	.271	2575	135.5	7.66	198	.668	.181	.849		"	1702	21	"	"	"	"	30.375	"	"	.01448	.001448	"	"	140	11.53	"	"	13.5	.000724	.638	2665	139.0	7.86	199	.663	.423	1.086		"	1711	22	"	"	"	"	30.345	"	"	.01478	.001478	"	"	138	11.72	"	"	14.8	.001110	.752	2700	140.5	7.95	195	.668	.503	1.171		"	1726	23	"	"	"	"	30.645	"	"	.01491	.001491	"	"	140	11.78	"	"	16.4	.001352	.908	2750	142.5	8.06	1982	.667	.604	1.261		"	1742
	4/10/46	1732	13	1200	160	212	35	30.105	ATM	543	.01011	.000646	.064	25	138	6.20	81	30.105	0	0	0	17.3	101.8	5.76	3265	403	0	403																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1741	14	"	"	"	"	"	"	"	.0103	.000659	"	"	142	6.30	"	"	7.5	.000274	.416	1785	104	5.88	327	403	.168	.571																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1745	15	"	"	"	"	"	"	544	.0105	.000671	"	"	141	6.39	"	"	8.5	.000366	.545	1855	106.8	6.04	330	399	.218	.617																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1754	16	"	"	"	"	"	"	"	.01069	.000684	"	"	"	6.48	"	"	10.0	.000516	.755	1935	110	6.23	3335	396	.298	.694																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1803	17	"	"	"	"	"	"	"	.01097	.000701	"	"	"	6.62	"	"	10.5	.000570	.813	1945	112.3	6.36	332	397	.322	.719																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	4/18/46	1222	1	"	"	"	33	30.375	"	546	.01095	.000767	.07	"	142	7.09	85	30.045	0	0	0	19.70	111.3	6.30	301	438	0	438																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1401	5	"	157	"	34	30.375	"	544	.01124	.000786	"	"	141	7.23	87	"	5.6	.000135	.172	2035	114	6.45	301	438	.075	.503																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1425	6	"	"	"	"	30.375	"	545	.01144	.000801	"	"	140	7.34	"	"	8.7	.000305	.481	2065	115.2	6.53	299	442	.212	.654																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1531	7	"	"	"	"	30.375	"	"	.01168	.000817	"	"	"	7.47	"	"	10.3	.000552	.676	2160	118.9	6.725	302	438	.246	.734																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1540	8	"	"	"	"	30.375	"	"	.01204	.000842	"	"	138	7.63	"	"	11.8	.000701	.833	2240	122.2	6.91	301	438	.365	.803																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1550	9	"	"	"	"	30.645	"	"	.01232	.000862	"	"	140	7.78	"	"	13.8	.000988	1.123	2385	127.8	7.10	307	432	.485	.917																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1232	2	"	160	"	"	30.645	"	"	.01261	.00101	.08	"	"	8.85	85	"	0	0	0	23.00	124.5	7.045	256	516	0	516																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1508	10	"	157	"	33	30.345	"	"	.01288	.001029	"	"	"	8.98	87	"	7.5	.000274	.266	2375	127.5	7.21	257	514	.137	.651																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1516	11	"	"	"	"	30.375	"	"	.01310	.001048	"	"	138	9.10	"	"	11.3	.000652	.622	2445	130.3	7.375	258	512	.318	.830																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1528	12	"	"	"	"	30.345	"	"	.01322	.001057	"	"	142	9.17	"	"	13.0	.000857	.812	2520	133.3	7.55	262	523	.408	.911																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1540	13	"	160	"	32	30.095	"	544	.01369	.001094	"	"	138	9.38	"	"	14.4	.001052	.962	2610	136.7	7.73	259	510	.491	1.001																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1549	14	"	"	"	"	30.375	"	"	.01400	.001122	"	"	140	9.55	"	"	15.7	.001244	1.108	2685	139.8	7.91	258	511	.567	1.078																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1302	3	"	157	"	35	30.045	"	542	.01343	.001209	.09	"	138	10.08	83	"	0	0	0	24.75	131.4	7.44	226	585	0	585																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1606	15	"	160	"	32	30.375	"	544	.01400	.001260	"	"	140	10.42	87	"	11.5	.000274	.535	2625	137.3	7.77	226	584	.312	.896																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1614	16	"	"	"	"	30.045	"	"	.01384	.001247	"	"	138	10.33	"	"	9.9	.000505	.405	2570	135.2	7.65	225	587	.238	.825																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1622	17	"	"	"	"	30.395	"	"	.01357	.001221	"	"	"	10.17	"	"	6.2	.000115	.152	2515	133.1	7.53	226	584	.089	.873																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1632	18	"	"	"	"	30.245	"	"	.01438	.001243	"	"	140	10.63	"	"	14.0	.000997	.771	2695	140.3	7.94	225	587	.452	1.039																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1639	19	"	"	"	"	30.045	"	"	.01466	.001319	"	"	138	10.78	"	"	15.5	.001245	.922	2740	142.2	8.05	224	590	.543	1.133																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1320	4	"	157	"	35	"	"	542	.01389	.001389	.10	"	139	11.18	85	"	0	0	0	25.25	133.5	7.55	1944	.662	0	.662																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1655	20	"	160	"	32	30.375	"	544	.01421	.001431	"	"	139	11.38	87	"	8.7	.000384	.271	2575	135.5	7.66	198	.668	.181	.849																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1702	21	"	"	"	"	30.375	"	"	.01448	.001448	"	"	140	11.53	"	"	13.5	.000724	.638	2665	139.0	7.86	199	.663	.423	1.086																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1711	22	"	"	"	"	30.345	"	"	.01478	.001478	"	"	138	11.72	"	"	14.8	.001110	.752	2700	140.5	7.95	195	.668	.503	1.171																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1726	23	"	"	"	"	30.645	"	"	.01491	.001491	"	"	140	11.78	"	"	16.4	.001352	.908	2750	142.5	8.06	1982	.667	.604	1.261																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
	"	1742	24	"	"	"	"	30.345	"	"	.01524	.001719	.064	"	"	6.74	86	"	12.0	.000725	1.008	29.5	114.7	6.49	331	.398	.462	.800																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														

M.I.T. AERO ENGINE LABORATORY

ENGINE *CFR* BORE $3\frac{1}{4}$ STROKE $4\frac{1}{2}$ COMPRESSION RATIO 6.6

Table IV

REMARKS	DATE	TIME	RPM	TEMPERATURE OIL	JAC	OIL PRES	P _i	P _E	T _i	AIR CONS.	FUEL CONS.	F _E A	S.A.	T _L	FUEL Roto	ROOM TEMP	BAR. CORR.	H ₂ O Roto	M _w	W/F	"H _g	IMEP	IHP	η _i	ISFC	ISWC	ISLC
	4/24/46	1304	1	158	212	33	37.84	ATM	542	.01267	.001267	.10	2.5	140	10.45	81	30.144	0	0	0	22.9	124	7.02	2035	.650	0	.650
	"	1310	2	"	"	"	37.54	"	544	.01280	.001280	"	"	138	10.54	"	"	9.3	.000446	349	23.25	125.5	7.10	2035	.649	.226	.875
	"	1320	3	"	"	"	37.24	"	"	.01291	.001291	"	"	140	10.61	"	"	11.9	.000713	553	23.45	126.2	7.14	203	.651	.360	1.011
	"	1330	4	"	"	"	36.94	"	"	.01310	.001310	"	"	"	10.73	80	"	13.4	.000912	696	23.8	127.7	7.22	202	.653	.455	1.108
	"	1339	5	"	"	"	36.44	"	"	.01330	.001330	"	"	"	10.84	79	"	14.5	.001067	802	24.15	129.2	7.32	202	.654	.525	1.179
	"	1353	6	"	"	"	38.64	"	545	.01234	.001111	.09	"	"	9.50	78	"	0	0	0	22.35	121.8	6.89	208	.581	0	.581
	"	1402	7	"	"	"	38.24	"	"	.01248	.001122	"	"	"	9.55	77	"	7.4	.000264	235	22.65	123.0	6.96	228	.581	.136	.717
	"	1414	8	"	"	"	38.04	"	"	.01268	.001139	"	"	138	9.65	"	"	9.6	.000477	419	23.3	125.6	7.10	229	.578	.242	.820
	"	1422	9	156	"	34	37.54	"	"	.01280	.001152	"	"	"	9.73	78	"	11.0	.00062	538	23.6	127.7	7.22	230	.575	.309	.884
	"	1431	10	"	"	"	37.04	"	"	.01306	.001175	"	"	140	9.88	80	"	12.9	.000843	717	24.3	129.7	7.33	229	.577	.414	.991
	"	1438	11	"	"	"	36.74	"	"	.01320	.001188	"	"	"	9.96	"	"	14.4	.001052	896	24.95	132.2	7.48	231	.572	.507	1.079
	"	1450	12	"	"	"	46.34	"	"	.01152	.000920	.08	"	142	8.24	81	"	0	0	0	24.9	116.2	6.675	266	.497	0	.497
	"	1458	13	"	"	"	39.84	"	"	.01173	.000933	"	"	140	8.29	"	"	7.0	.000228	245	21.6	118.9	6.725	264	.500	.122	.622
	"	1514	14	"	"	"	39.44	"	546	.01197	.000956	"	"	"	8.46	"	"	8.4	.000355	371	22.0	120.5	6.82	262	.505	.187	.692
	"	1523	15	"	"	"	38.94	"	"	.01233	.000978	"	"	142	8.62	"	"	12.5	.000792	81	22.85	123.9	7.00	262	.503	.407	.910
	"	1531	16	"	"	"	38.44	"	"	.01249	.000998	"	"	140	8.77	"	"	14.0	.000998	110	23.7	127.2	7.20	264	.449	.449	.898
	"	1541	17	"	"	"	39.14	"	"	.01212	.000969	"	"	"	8.55	"	"	10.2	.000540	557	22.55	123.6	6.94	262	.502	.280	.782
	"	1548	18	"	"	"	38.94	"	"	.01008	.000705	.07	"	"	6.65	"	"	0	0	0	17.55	102.8	5.82	303	.427	0	.427
	"	1613	19	"	"	"	38.24	"	547	.01032	.000721	"	"	"	6.75	"	"	7.0	.000228	316	18.3	105.7	5.975	304	.434	.137	.571
	"	1619	20	"	"	"	37.54	"	"	.01056	.000739	"	"	139	6.88	"	"	10.1	.000530	717	18.95	108.5	6.14	305	.432	.311	.714
	"	1628	21	"	"	"	36.74	"	"	.01087	.000760	"	"	140	7.04	82	"	11.5	.000674	897	19.5	110.5	6.25	302	.428	.388	.826
	"	1637	22	"	"	"	37.84	"	"	.01043	.000730	"	"	"	6.83	"	"	8.2	.000337	461	19.55	106.8	6.04	303	.405	.201	.624
	"	1710	23	"	"	"	37.24	"	548	.00881	.000565	.064	"	"	5.57	83	"	0	0	0	14.65	91.1	5.16	335	.394	0	.394
	"	1720	24	"	"	"	36.34	"	"	.009025	.000577	"	"	"	5.67	"	"	5.4	.000118	205	15.3	93.6	5.30	337	.392	.0802	.472
	"	1726	25	"	"	"	35.64	"	"	.00917	.000587	"	"	"	5.74	"	"	7.6	.000383	492	15.9	96.0	5.43	340	.390	.188	.578
	"	1732	26	"	"	"	34.84	"	"	.00937	.000600	"	"	"	5.84	"	"	8.5	.000367	612	16.1	97.0	5.49	336	.393	.241	.634
	"	1742	27	"	"	"	33.94	"	"	.00956	.000612	"	"	"	5.93	"	"	10.1	.00053	866	16.6	99.0	5.60	336	.393	.341	.734

M.I.T. AERO ENGINE LABORATORY

ENGINE *CFR* BORE $3\frac{1}{4}$ STROKE $4\frac{1}{2}$ COMPRESSION RATIO 7.0

Table V

REMARKS	DRIE TIME	RPM	TEMP. OIL	TEMP. JAC	OIL PRESS	P _i	P _e	T _i	AIR CONS.	FUEL CONS.	F/A	S.A.	T _i	Fuel Roto	Room TEMP	BAR. CORR.	H ₂ O Roto	M _w	W/F	"H _g	IMEP	IHP	η _i	ISFC	ISWC	ISLC
	4/23/46	1440	160	212	24	34.539	ATM	545	.00801	.000514	.064	25	140	5.15	87		0	0	0	13.0	84.4	4.77	.340	.388	0	.388
	"	1452	"	159	32	34.124	"	"	.00838	.000536	"	"	"	5.33	"	"	6.7	.000213	.397	13.9	88.0	4.98	.341	.387	.154	.541
	"	1459	"	158	33	34.229	"	"	.00866	.000554	"	"	"	5.48	"	"	8.1	.000327	.591	14.3	89.6	5.07	.335	.393	.232	.625
	"	1507	"	"	31	34.304	"	"	.00905	.000579	"	"	"	5.69	88	"	9.8	.000496	.873	15.3	93.6	5.30	.3355	.393	.337	.730
	"	1518	"	"	31	34.204	"	"	.00934	.000598	"	"	"	5.83	"	"	11.8	.000698	1.168	16.1	96.8	5.48	.336	.393	.458	.851
	"	1524	"	"	31	34.609	"	546	.00950	.000608	"	"	"	5.92	"	"	12.6	.000803	1.322	16.32	97.7	5.53	.3335	.396	.523	.919
	"	1536	"	"	"	"	"	"	.00946	.000660	.07	"	"	6.31	"	"	0	0	0	16.0	96.6	5.47	.304	.435	0	.435
	"	1545	"	"	"	34.209	"	"	.00968	.000677	"	"	"	6.41	"	"	8.2	.000336	.496	16.8	99.8	5.65	.306	.432	.214	.646
	"	1555	"	"	"	34.439	"	"	.00991	.000694	"	"	"	6.56	"	"	9.5	.000465	.671	17.4	102.1	5.78	.305	.432	.290	.722
	"	1604	"	"	"	34.504	"	"	.01013	.000709	"	"	"	6.68	"	"	10.8	.000600	.847	17.9	104.2	5.90	.305	.433	.366	.799
	4/24/46	1336	"	"	32	34.963	"	543	.01054	.000738	"	"	"	6.88	83	"	13.3	.000900	1.220	19.5	110.4	6.25	.310	.425	.519	.944
	"	1401	"	"	34	34.563	"	545	.01029	.000720	"	"	"	6.75	88	"	11.8	.000702	.975	18.7	107.3	6.075	.3096	.427	.416	.843
	4/23/46	1625	"	"	33	34.409	"	547	.01079	.000862	.08	"	"	7.78	"	"	0	0	0	19.2	109.4	6.195	.259	.509	0	.509
	4/24/46	1423	"	"	35	34.573	"	546	.01097	.000877	"	"	"	7.89	"	"	9.6	.000477	.544	20.0	112.5	6.36	.266	.496	.270	.766
	"	1430	"	"	"	34.263	"	"	.01118	.000893	"	"	"	8.0	"	"	11.0	.000618	.692	20.75	115.6	6.54	.268	.492	.340	.832
	"	1435	"	"	"	34.763	"	"	.01133	.000907	"	"	"	8.1	"	"	12.2	.000794	.931	21.0	116.7	6.40	.267	.495	.412	.907
	"	1442	"	"	34	34.813	"	"	.01140	.000911	"	"	"	8.13	"	"	13.0	.000857	.940	21.3	117.8	6.66	.268	.492	.463	.955
	"	1452	"	"	"	34.263	"	"	.01182	.000945	"	"	"	8.38	"	"	14.7	.001098	1.160	22.3	121.7	6.88	.267	.495	.575	1.070
	"	1455	"	"	"	34.363	"	"	.01147	.001027	.09	"	"	8.97	86	"	0	0	0	20.8	115.8	6.55	.234	.565	0	.565
	"	1423	"	155	35	34.063	"	"	.01162	.001046	"	"	"	9.08	85	"	6.9	.000222	.211	21.1	117.9	6.62	.232	.568	.8196	.888
	"	1453	"	"	"	34.563	"	"	.01191	.001072	"	"	"	9.24	84	"	13.5	.000924	.862	22.5	122.5	6.93	.237	.557	.480	1.017
	"	1708	"	"	"	34.063	"	"	.01181	.001063	"	"	"	9.18	"	"	10.3	.000532	.519	21.4	120.0	6.79	.234	.564	.242	.856
	"	1717	"	"	"	34.463	"	"	.01206	.001084	"	"	"	9.32	"	"	15.0	.00114	1.052	22.7	123.3	6.98	.230	.560	.588	1.148
	"	1730	"	"	"	34.963	"	"	.01218	.001294	"	"	"	9.38	"	"	12.0	.001442	1.318	22.9	124.2	7.03	.236	.561	.739	1.300
	4/25/46	1228	"	"	31	34.75	"	547	.01175	.001175	.10	"	138	9.89	87	"	0	0	0	20.75	115.6	6.57	.204	.6375	0	.638
	"	1240	"	"	32	34.55	"	"	.01188	.001198	"	"	140	9.96	"	"	8.3	.000347	.292	21.1	117.0	6.42	.204	.646	.189	.835
	"	1250	"	"	"	34.15	"	"	.01211	.001211	"	"	142	10.1	"	"	13.0	.000858	.708	21.7	119.3	6.75	.2045	.646	.458	1.104
	"	1300	"	"	"	34.35	"	"	.01248	.001248	"	"	140	10.34	"	"	16.3	.001334	1.068	22.4	122.1	6.91	.203	.650	.496	1.346
	"	1312	"	"	33	34.25	"	"	.01200	.001200	"	"	138	10.04	"	"	12.1	.00053	.710	21.7	118.1	6.08	.204	.647	.286	.933

M.I.T. AERO ENGINE LABORATORY

ENGINE CFR

BORE 3 1/4 STROKE 4 1/2

COMPRESSION RATIO

7.4

Table VI

REMARKS	DATE	TIME	RPM	TEMPERATURE		OIL PRES.	P _i	P _E	T _i	AIR CONS.	FUEL CONS.	F/A	S.A.	T _i	FUEL ROTO	ROOM TEMP.	BAR. CORR.	H ₂ O ROTO	M _W	W/F	"Hg	IMEP	IHP	η _i	ISFC	ISWC	ISLG
				OIL JAC	OIL																						
	4/25/46	1337	6	1200	160	33	40.25	ATM	547	.01072	.001072	.10	2.5	140	9.25	89	29.85	0	0	0	18.75	107.5	6.08	.208	.635	0	.635
	"	1347	7	"	158	34	40.15	"	"	.01088	.001088	"	"	"	9.35	"	"	6.3	.000182	.176	18.85	108.0	6.12	.2063	.640	.113	.753
	"	1353	8	"	"	"	40.05	"	"	.01108	.001108	"	"	138	9.47	"	"	9.0	.000413	.373	19.15	109.1	6.175	.2045	.646	.241	.887
	"	1401	9	"	"	"	39.65	"	"	.01133	.001133	"	"	"	9.63	"	"	12.9	.000844	.745	19.9	112.2	6.295	.204	.648	.483	.151
	"	1410	10	"	"	"	39.45	"	"	.01153	.001153	"	"	140	9.74	"	"	14.4	.001052	.913	20.35	114.0	6.455	.205	.644	.588	1.232
	"	1425	11	"	"	"	40.95	"	"	.01064	.000960	.09	"	"	8.49	"	"	0	0	0	18.8	107.7	6.09	.233	.567	0	.567
	"	1435	12	"	"	"	40.75	"	"	.01080	.000972	"	"	"	8.57	"	"	7.6	.000283	.291	19.3	109.7	6.21	.234	.564	.164	.728
	"	1442	13	"	"	"	40.45	"	"	.01102	.000991	"	"	"	8.72	88	"	10.4	.000562	.567	19	111.1	6.29	.233	.567	.322	.889
	"	1452	14	"	"	"	40.25	"	"	.01132	.001016	"	"	138	8.92	"	"	14.1	.00101	.994	20.6	115	6.51	.235	.562	.559	1.121
	"	1458	15	"	"	"	39.65	"	"	.01156	.001040	"	"	"	9.05	"	"	17.5	.001524	1.465	21.3	117.7	6.66	.2345	.562	.824	1.386
	"	1520	16	"	"	"	40.65	"	"	.00953	.000762	.08	"	142	7.05	"	"	0	0	0	16.6	99.1	5.61	.270	.489	0	.489
	"	1531	17	"	"	"	40.15	"	"	.00981	.000785	"	"	140	7.23	"	"	7.3	.000242	.309	17	100.6	5.69	.266	.497	.153	.650
	"	1540	18	"	"	"	39.85	"	"	.01000	.000800	"	"	"	7.34	"	"	9.1	.000424	.531	17.55	102.8	5.82	.266	.495	.262	.757
	"	1555	19	"	"	"	39.55	"	"	.01041	.000833	"	"	"	7.58	"	"	11.2	.000640	.769	19.45	106.3	6.02	.265	.498	.383	.881
	"	1608	20	"	"	"	38.55	"	"	.01066	.000852	"	"	"	7.72	87	"	13.5	.000925	1.086	19.65	111.2	6.295	.271	.488	.529	1.017
	"	1618	21	"	"	"	38.15	"	"	.01089	.000871	"	"	138	7.84	"	"	14.3	.00104	1.144	20.1	113	6.40	.269	.490	.585	1.075
	"	1640	22	"	"	"	29.85	"	548	.00812	.000568	.07	"	"	5.60	"	"	0	0	0	13.1	85	4.815	.311	.425	0	.425
	"	1647	23	"	"	"	"	"	"	.00833	.000583	"	"	142	5.72	"	"	5.6	.000135	.232	13.6	87	4.925	.310	.427	.0987	.526
	"	1655	24	"	"	"	"	"	"	.00852	.000596	"	"	"	5.81	"	"	9.3	.000348	.544	14.25	89.5	5.07	.312	.423	.247	.670
	"	1659	25	"	"	"	"	"	"	.00885	.000619	"	"	140	5.99	"	"	10.3	.000550	.889	14.9	92	5.21	.3085	.428	.380	.868
	"	1707	26	"	"	"	"	"	"	.00912	.000638	"	"	"	6.13	88	"	12.5	.000793	1.242	15.45	94.3	5.34	.307	.430	.535	.965
	"	1716	27	"	160	"	"	"	549	.00693	.000443	.064	"	142	4.49	89	"	0	0	0	16	72.7	4.112	.340	.388	0	.388
	"	1724	28	"	"	"	"	"	"	.00709	.000454	"	"	143	4.59	"	"	5.2	.000602	.225	10.55	74.8	4.23	.342	.386	.0867	.473
	"	1732	29	"	"	"	"	"	"	.00727	.000465	"	"	"	4.69	"	"	7.3	.000255	.549	11.1	77.0	4.36	.344	.384	.211	.595
	"	1741	30	"	"	"	"	"	"	.00756	.000484	"	"	140	4.87	"	"	9.0	.000413	.854	11.75	79.5	4.50	.341	.387	.331	.718
	"	1748	31	"	"	"	"	"	"	.00784	.000502	"	"	"	5.04	"	"	10.4	.000560	1.116	12.1	81	4.58	.335	.394	.439	.833
	9/2/46	1212	1	"	156	"	36.78	"	550	.01026	.000474	.11	"	"	10	87	29.87	0	0	0	18.8	107	6.05	.186	.711	0	.711
	"	1225	2	"	"	"	38.28	"	"	.0066	.00047	.15	"	"	8.86	"	"	"	"	"	18.7	109.3	6.07	.220	.602	"	.602
	"	1235	3	"	"	"	34.78	"	"	.00221	.00047	.025	"	"	7.85	"	"	"	"	"	17.7	123.4	5.85	.246	.526	"	.526
	"	1250	4	"	"	"	40.07	"	"	.00813	.00047	.035	"	11	6.38	"	"	"	"	"	14.8	91.7	5.19	.257	.702	"	.702

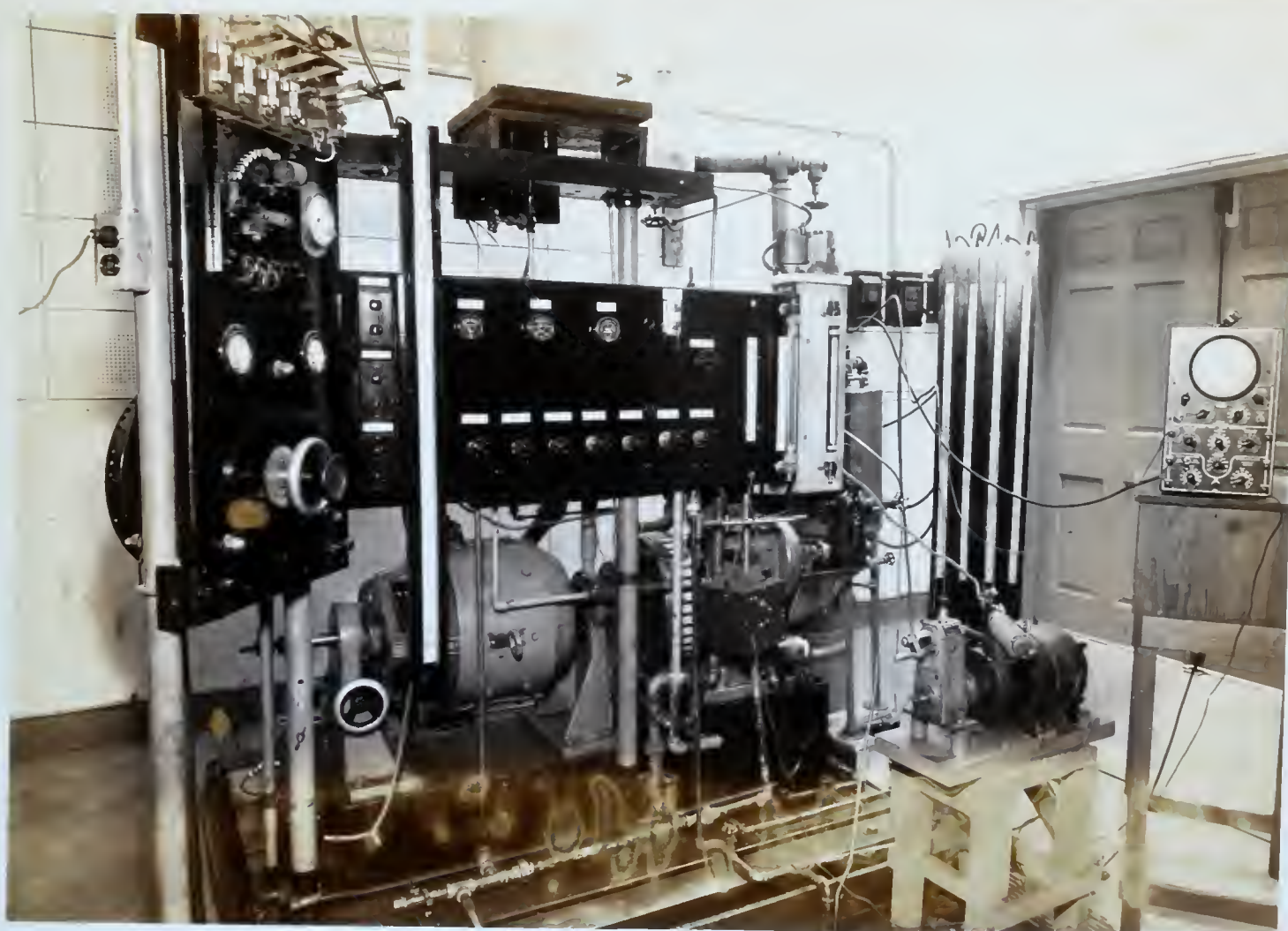


FIG. 1.

FRONT VIEW SHOWING GENERAL ARRANGEMENT
OF APPARATUS



FIG. 1.
FRONT VIEW SHOWING GENERAL ARRANGEMENT
OF APPARATUS

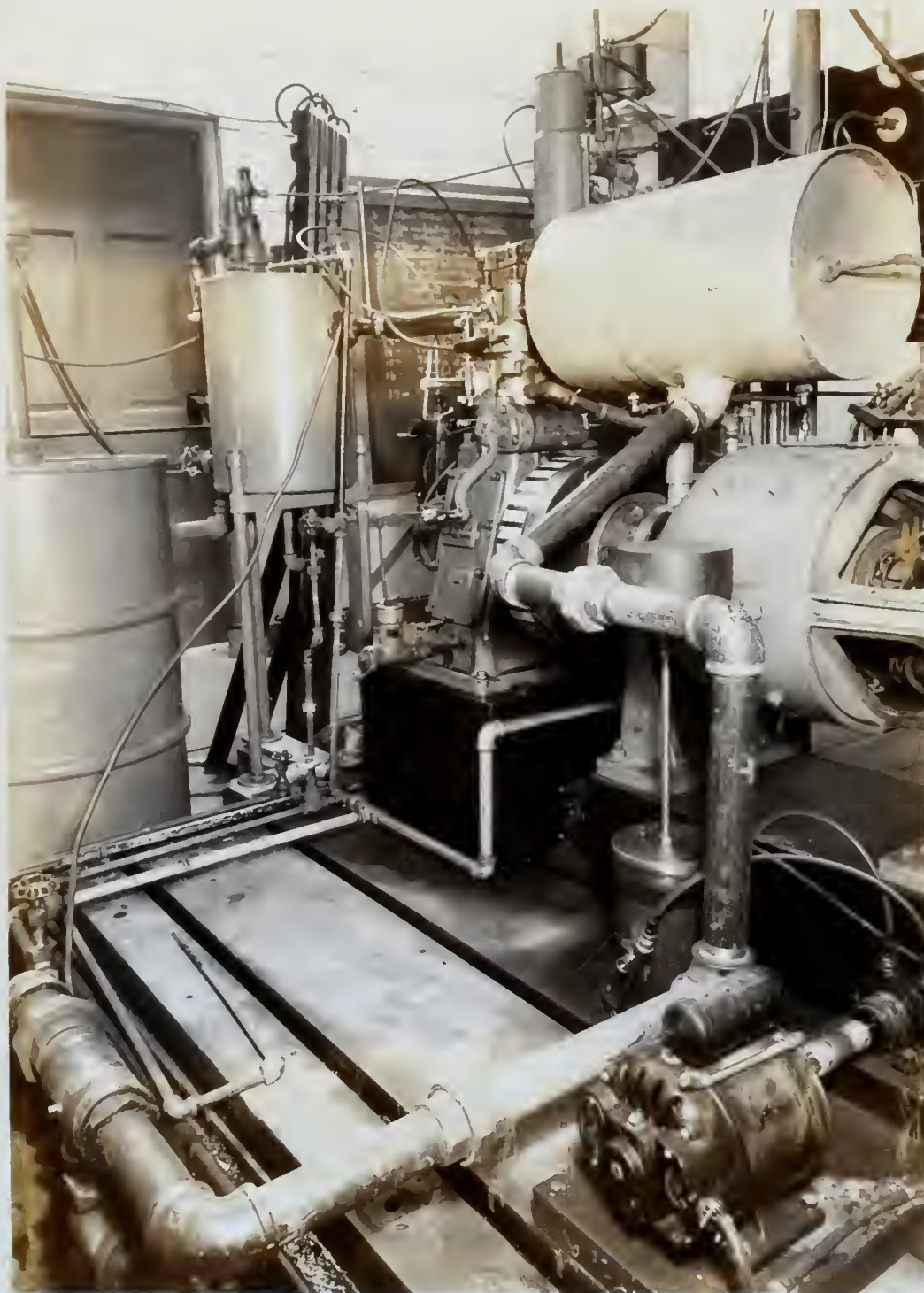


FIG. 2.
REAR VIEW SHOWING GENERAL ARRANGEMENT
OF APPARATUS



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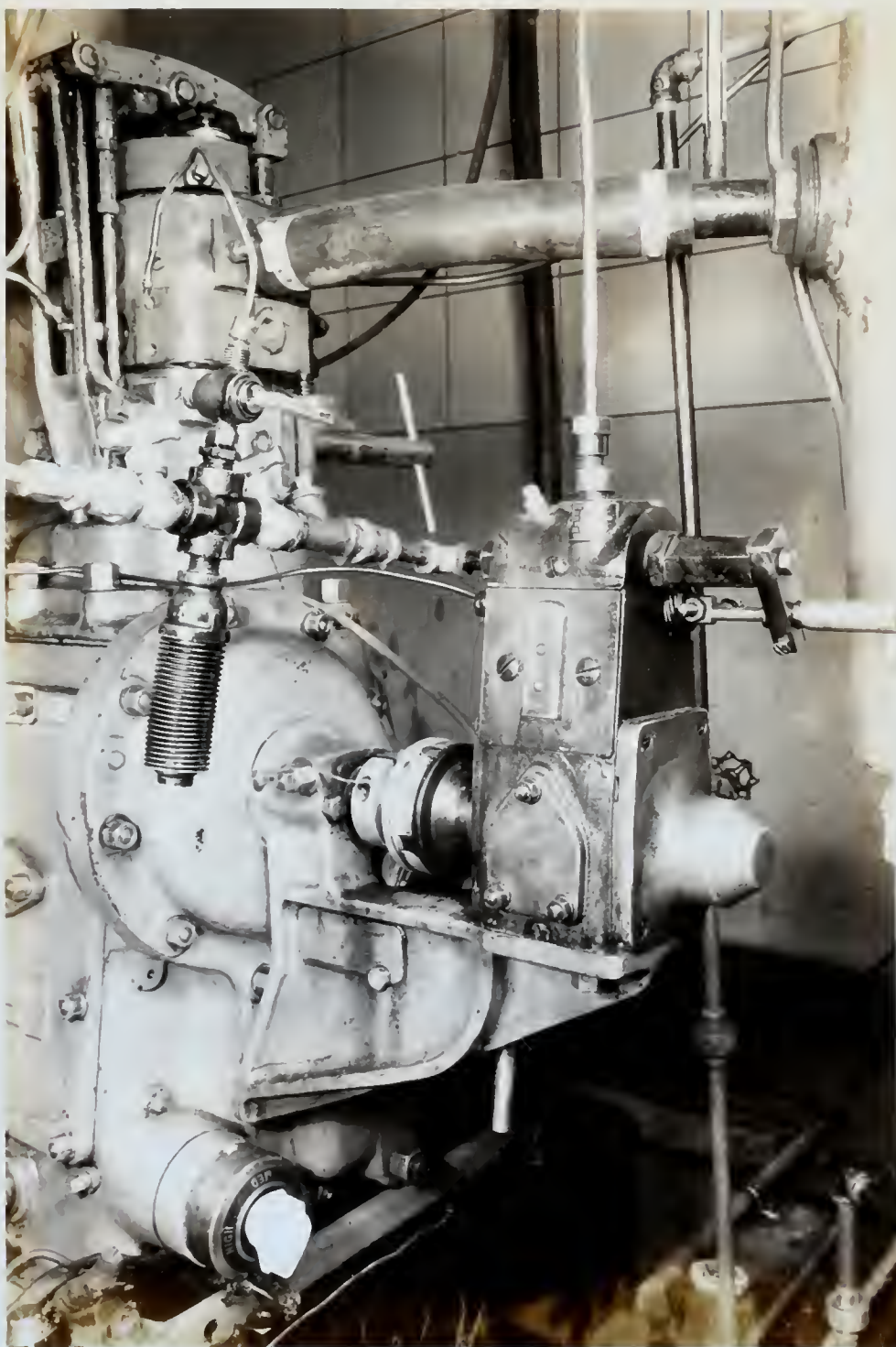


FIG. 3.

BOSCH PUMP USED FOR WATER INJECTION



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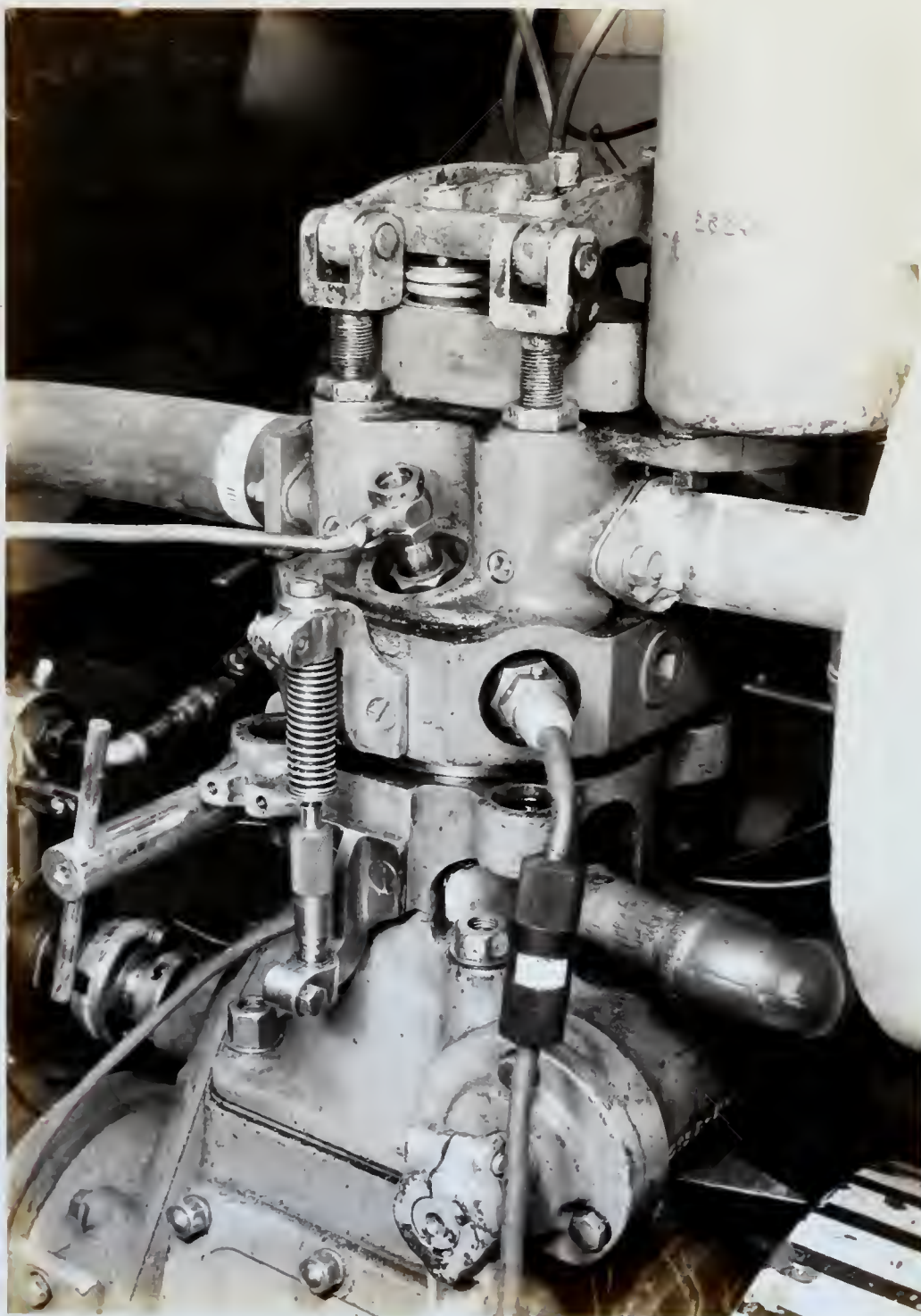


FIG. 4.
LOCATION OF WATER INJECTION NOZZLE
AND COMPRESSION RATIO ADJUSTMENT



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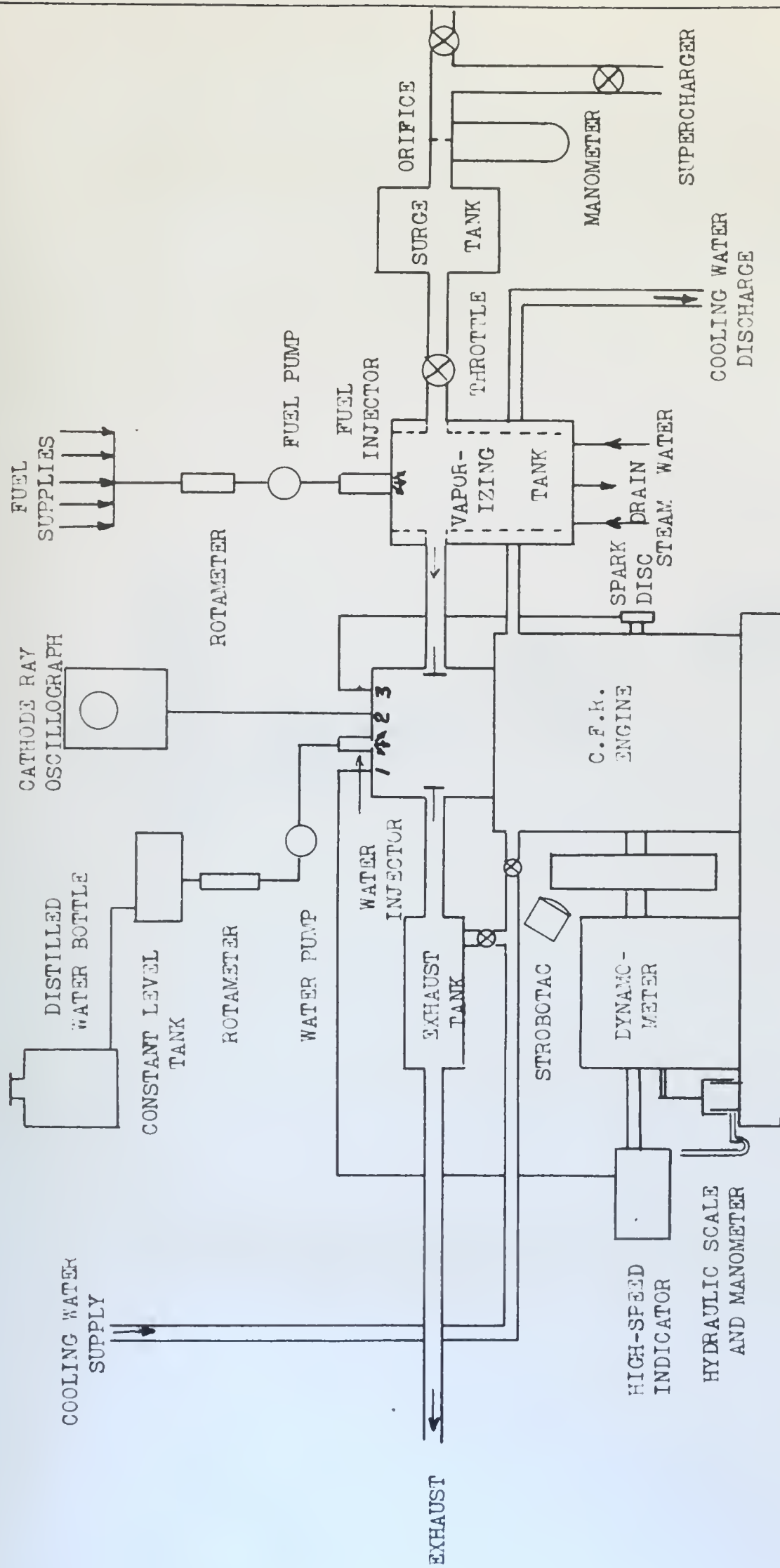


Fig. 5.

1. INDICATOR PICKUP
2. RATE OF PRESSURE PICKUP
3. SPARK PLUG

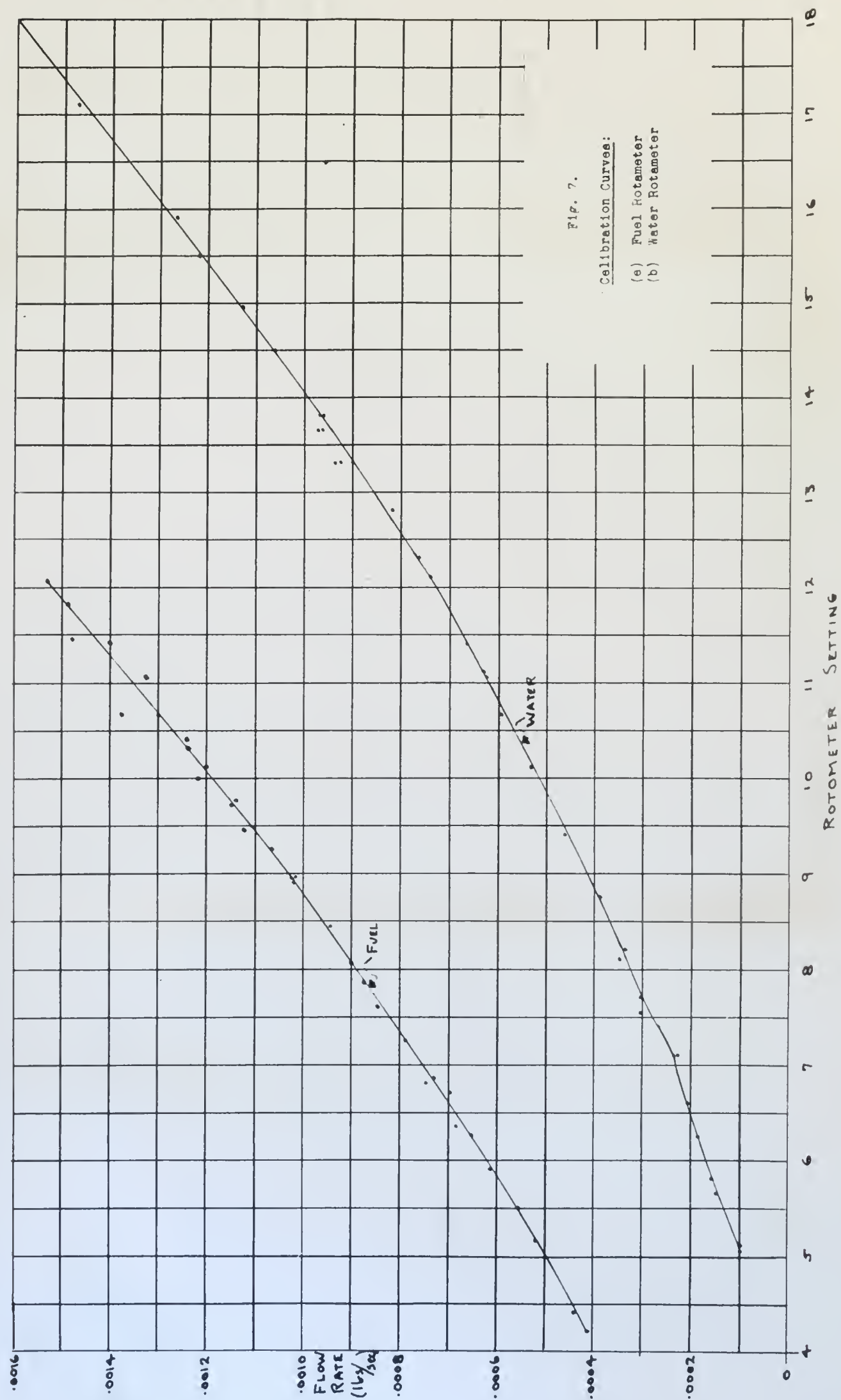
SLOAN LABORATORY
EXPERIMENTAL C.F.R. ENGINE SETUP

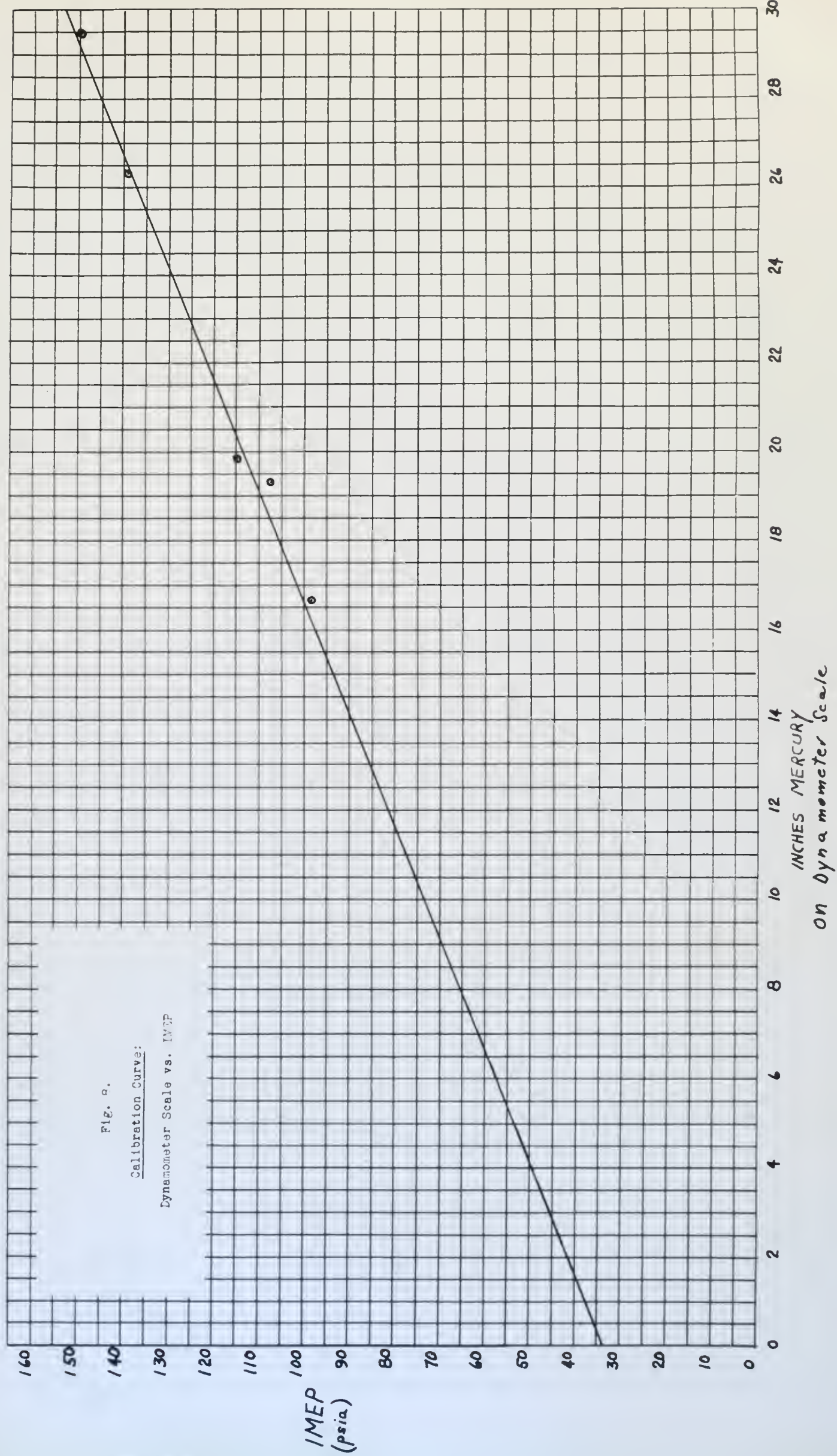


FIG. 6.

REPLACES EC 5051 NOZZLE USED
FOR WATER INJECTION DISASSEMBLED

THE
BUREAU OF THE
INTERNAL SECURITY





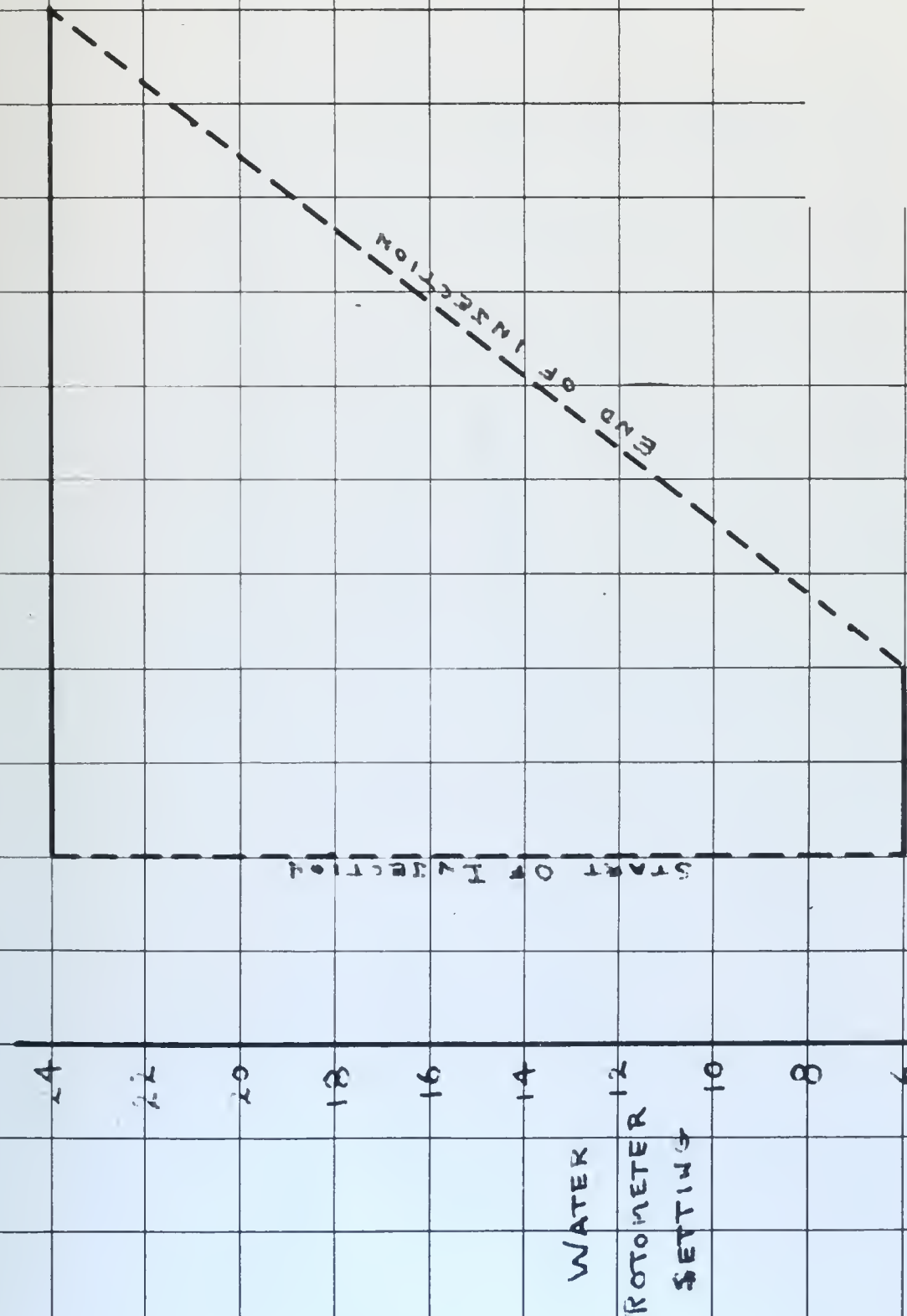


Fig. 9.
Variation of length of
water injection period
with water flow.

T.C.
10 DEGREES AFTER TOP CENTER, X.
50
40
30
20
10
0

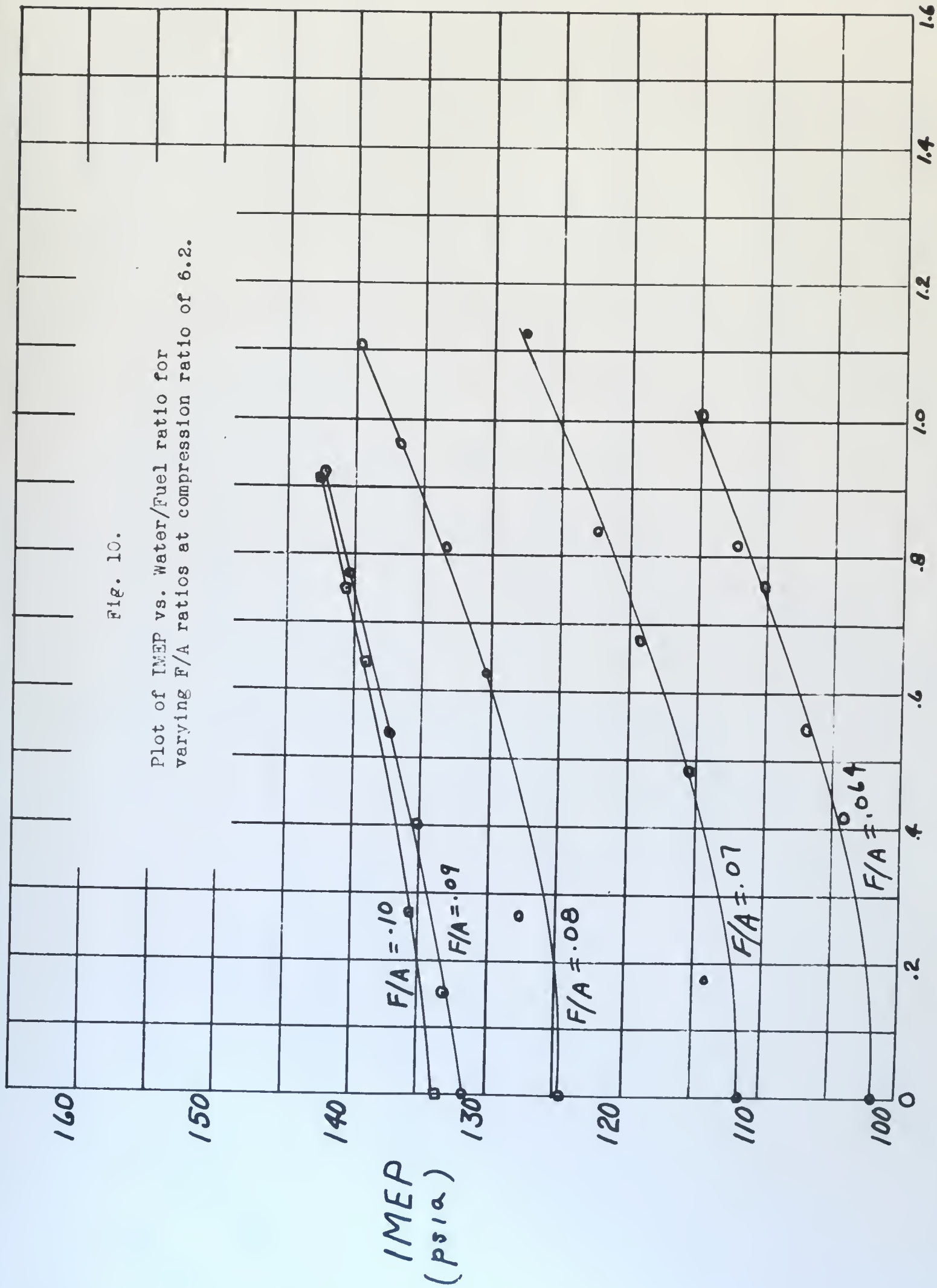


Fig. 10.

Plot of IMEP vs. Water/Fuel ratio for
varying F/A ratios at compression ratio of 6.2.

$$\frac{W}{F} = \left(\frac{\text{lbs. H}_2\text{O}}{\text{lb. Fuel}} \right)$$

Fig. 12.

Plot of IMEP vs. Water/Fuel ratio for
varying F/A ratios at compression ratio 7.0.

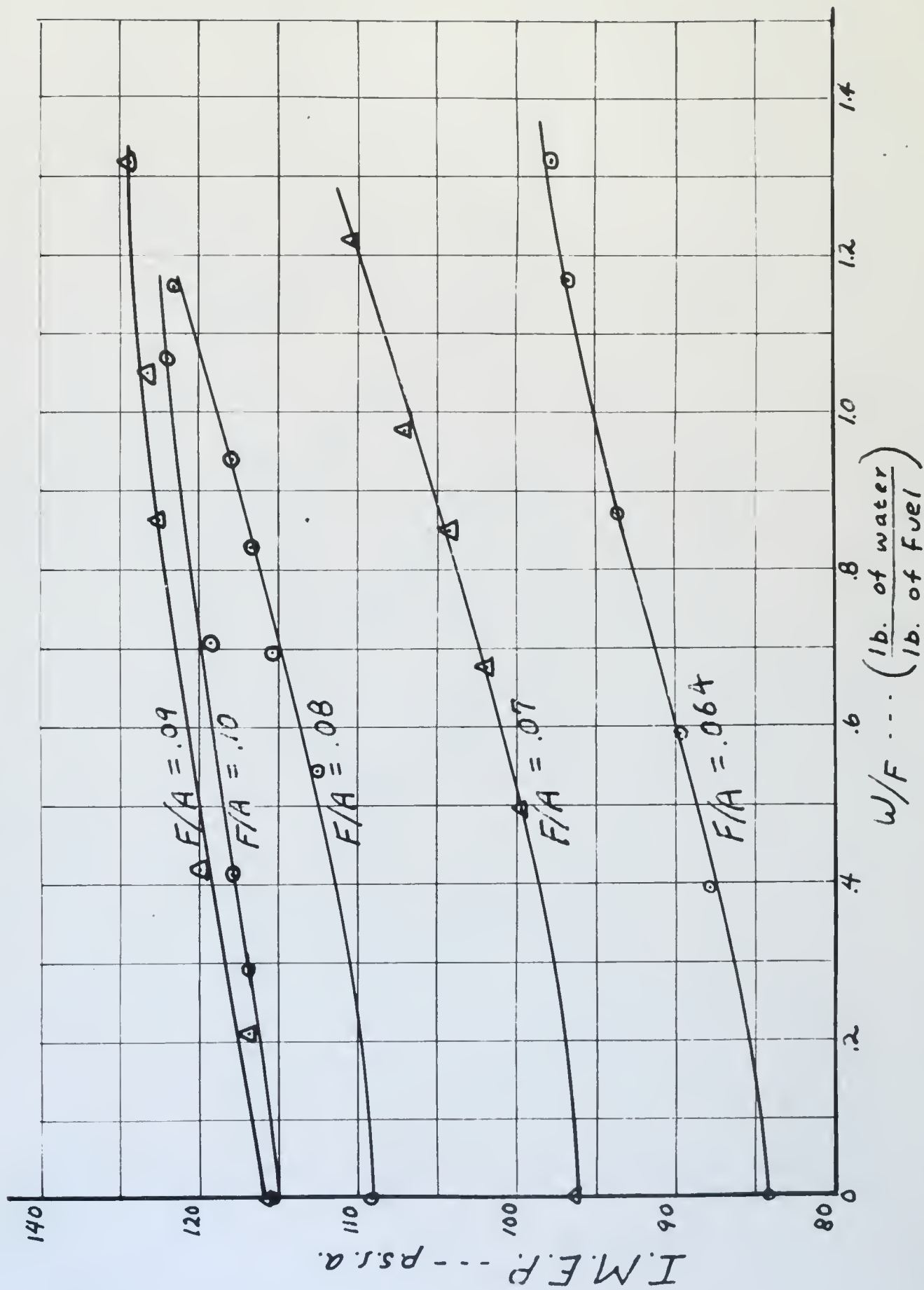
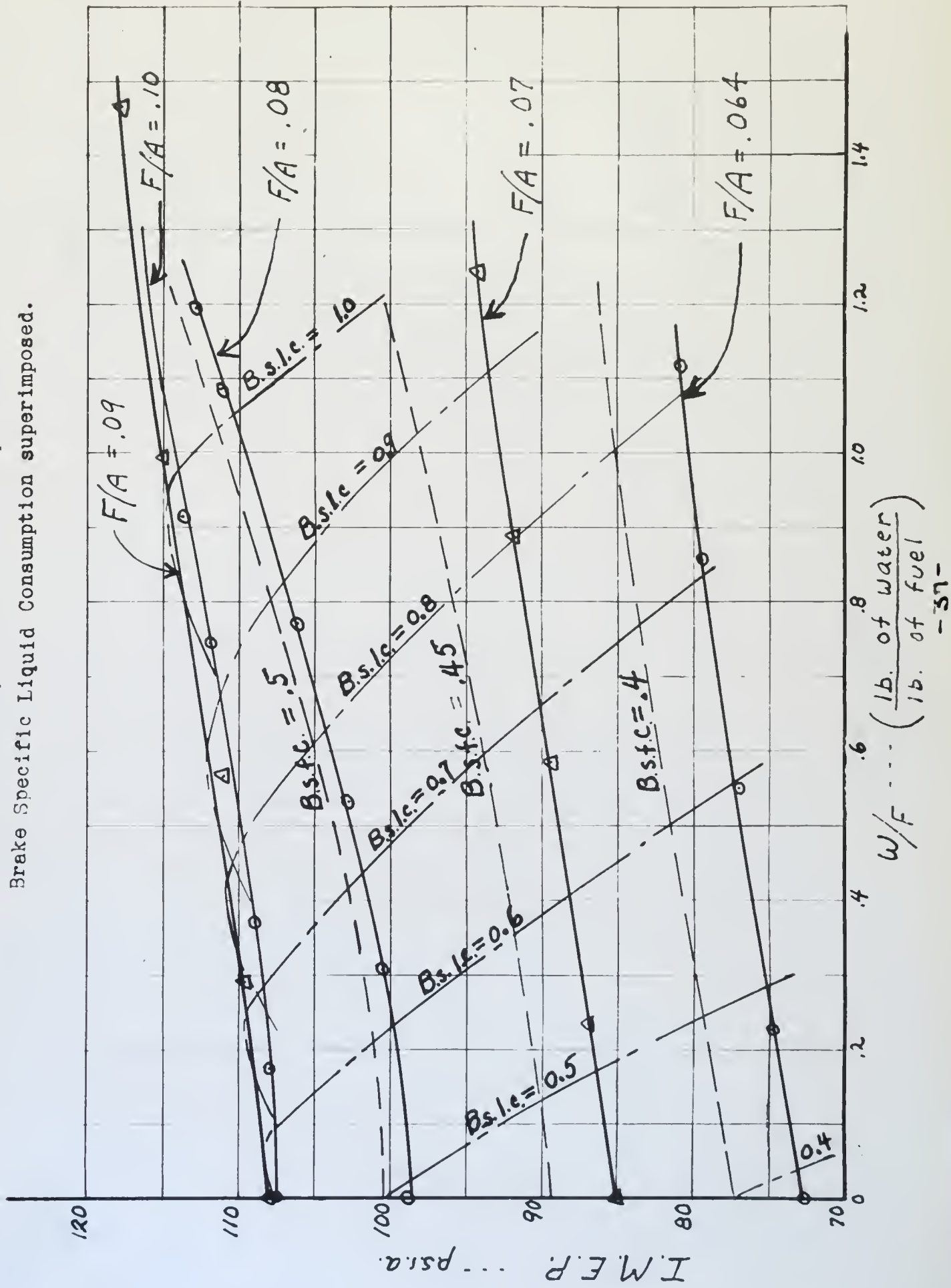
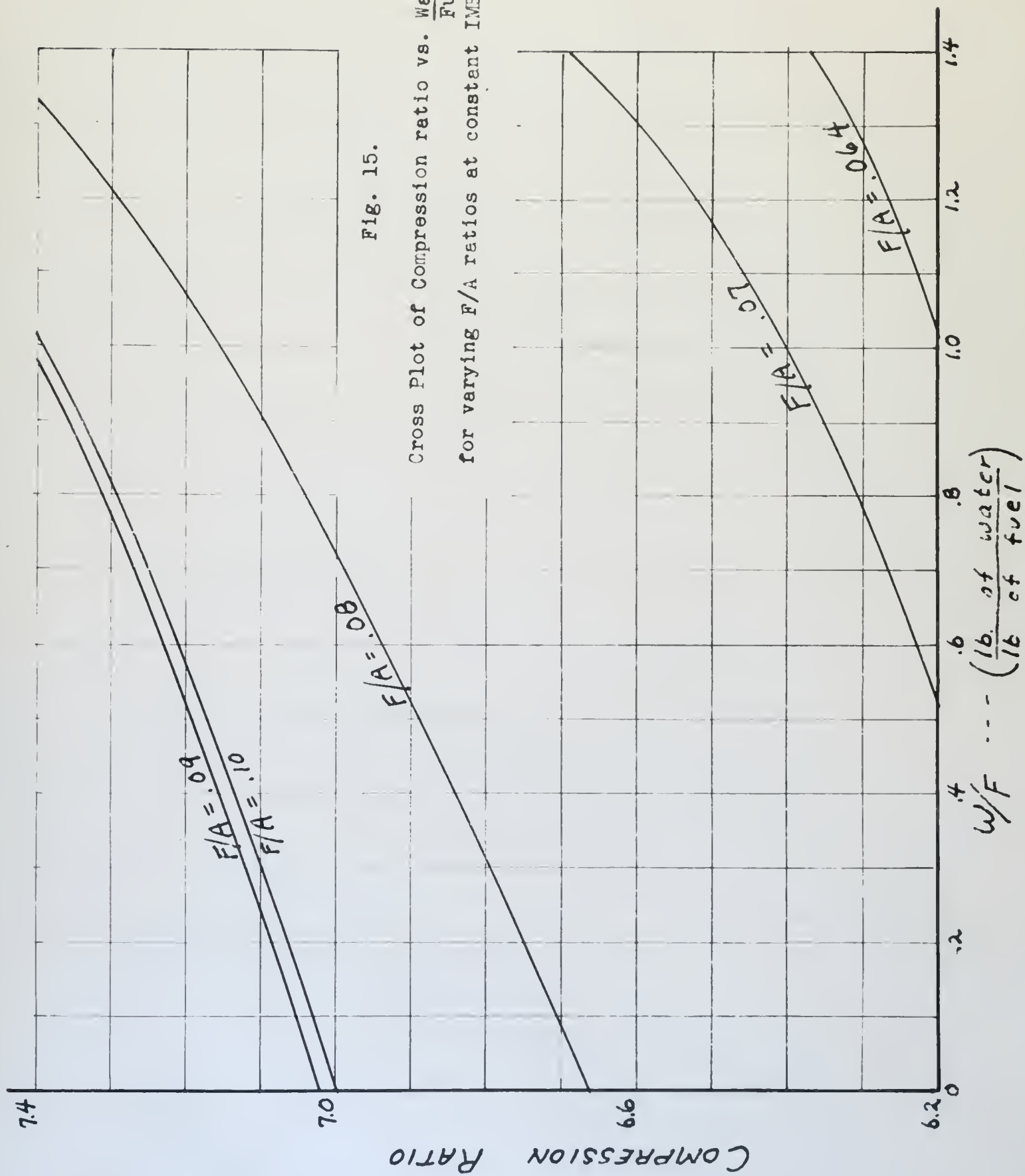


Fig. 13.

Plot of IMEP vs. Water/Fuel ratio for varying F/A ratios at compression ratio 7.4. Lines of constant Brake Specific Fuel Consumption and Brake Specific Liquid Consumption superimposed.





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